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Sensor Data Transmission from a Physical Twin to a Digital Twin

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 08.04.2019
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Title of thesis Sensor Data Transmission from a Physical Twin to a Digital Twin

Degree programme Master's Programme in Mechanical Engineering

Thesis supervisor Prof. Kari Tammi

Thesis advisor(s) M.Sc. (Tech.) Juuso Autiosalo

Date 08.04.2019 **Number of pages** 90+15 **Language** English

Abstract

A digital twin is a digital counterpart of a physical thing such as a machine. The term digital twin was first introduced in 2010. Thereafter, it has received an extensive amount of interest because of the numerous benefits it is expected to offer throughout the product life cycle. Currently, the concept is developed by the world's largest companies such as Siemens. The purpose of this thesis is to examine which application layer protocols and communication technologies are the most suitable for the sensor data transmission from a physical twin to a digital twin. In addition, a platform enabling this data transmission is developed.

As the concept of a digital twin is relatively new, a comprehensive literature view on the definition of a digital twin in scientific literature is presented. It has been found that the vision of a digital twin has evolved from the concepts of 'intelligent products' presented at the beginning of the 2000s. The most widely adopted definition states that a digital twin accurately mirrors the current state of its corresponding twin. However, the definition of a digital twin is not yet standardized and varies in different fields.

Based on the literature review, the communication needs of a digital twin are derived. Thereafter, the suitability of HTTP, MQTT, CoAP, XMPP, AMQP, DDS, and OPC UA for sensor data transmission are examined through a literature review. In addition, a review of 4G, 5G, NB-IoT, LoRa, Sigfox, Bluetooth, Wi-Fi, Z-Wave, ZigBee, and WirelessHART is presented.

A platform for the management of the sensors is developed. The platform narrows the gap between the concept and realization of a digital twin by enabling sensor data transmission. The platform allows easy addition of sensors to a physical twin and provides an interface for their configuration remotely over the Internet. It supports multiple sensor types and application protocols and offers both web user interface and REST API.

Keywords Digital twin, IoT, communication, application layer protocol, wireless networks

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Työn nimi Anturidatan lähettäminen fyysiseltä kaksoselta digitaaliselle kaksoselle

Koulutusohjelma Konetekniikan maisteriohjelma

Työn valvoja Prof. Kari Tammi

Työn ohjaaja(t) DI Juuso Autiosalo

Päivämäärä 08.04.2019 **Sivumäärä** 90+15 **Kieli** Englanti

Tiivistelmä

Digitaalinen kaksonen on fyysisen tuotteen digitaalinen vastinkappale, joka sisältää tiedon sen nykyisestä tilasta. Digitaalisen kaksosen käsite otettiin ensimmäisen kerran käyttöön vuonna 2010. Sen jälkeen digitaalinen kaksonen on saanut paljon huomiota, ja sitä ovat lähteneet kehittämään maailman suurimmat yritykset, kuten Siemens. Tämän työn tarkoituksena tutkia, mitkä sovelluskerroksen protokollat ja langattomat verkot soveltuvat parhaiten anturien keräämän datan lähettämiseen fyysiseltä kaksoselta digitaaliselle kaksoselle. Sen lisäksi työssä esitellään alusta, joka mahdollistaa tämän tiedonsiirron.

Digitaalisen kaksosesta esitetään laaja kirjallisuuskatsaus, joka luo pohjan työn myöhemmille osioille. Digitaalisen kaksosen konsepti pohjautuu 2000-luvun alussa esiteltyihin ajatuksiin ”älykkäistä tuotteista”. Yleisimmän käytössä olevan määritelmän mukaan digitaalinen kaksonen heijastaa sen fyysisen vastinparin tämän hetkistä tilaa. Määritelmä kuitenkin vaihtelee eri alojen välillä eikä se ole vielä vakiintunut tieteellisessä kirjallisuudessa.

Kirjallisuuskatsauksen avulla johdetaan digitaalisen kaksosen kommunikaatiotarpeet. Sen jälkeen arvioidaan seuraavien sovelluskerroksen protokollien soveltuvuutta anturidatan lähettämiseen kirjallisuuskatsauksen avulla: HTTP, MQTT, CoAP, XMPP, AMQP, DDS ja OPC UA. Myös seuraavien langattomien verkkojen soveltuvuutta tiedonsiirtoon tutkitaan: 4G, 5G, NB-IoT, LoRaWAN, Sigfox, Bluetooth, Wi-Fi, Z-Wave, ZigBee ja WirelessHART.

Osana työtä kehitettiin myös ohjelmistoalusta, joka mahdollistaa anturien hallinnan etänä Internetin välityksellä. Alusta on pieni askel kohti digitaalisen kaksosen käytännön toteutusta, sillä se mahdollistaa tiedon keräämisen fyysisestä vastinkappaleesta. Sen avulla sensorien lisääminen fyysiseen kaksoseen on helppoa, ja se tukee sekä useita sensorityyppejä että sovelluskerroksen protokollia. Alusta tukee REST API –rajapintaa ja sisältää web-käyttöliittymän.

Avainsanat Digitaalinen kaksonen, IoT, kommunikaatio, sovellus kerroksen protokollat, langattomat verkot

Preface

I would like to thank my supervisor Professor Kari Tammi and instructor Juuso Autiosalo for their valuable advices and guidance through the writing of this thesis. Thank should also go to Professor Petri Kuosmanen, who initially made me interested in the concept of a digital twin. I would like to acknowledge the assistance of Heikki Timonen for his advices in coding and writing and Ivar Koene for his help with microcontrollers. I would also like to thank the members of DigiTwin consortium for their ideas and visions of a digital twin.

Finally, special thanks to my friends and family, who have supported me through the writing of this thesis.

Espoo 08.04.2019

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Abbreviations

AES	Advanced Encryption Standard
AMQP	Advanced Message Queuing Protocol
CoAP	Constrained Application Protocol
CPS	Cyber-Physical System
CPPS	Cyber-Physical Productions System
C2PS	Cloud-Based Cyber-Physical System
DDS	Data Distribution Service
DES	Data Encryption Standard
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
IIoT	Industrial Internet of Things
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
M2M	Machine-to-Machine
MES	Manufacturing Execution System
MQTT	Message Queuing Telemetry Transport
MQTT-SN	MQTT for Sensor Networks
NB-IoT	Narrowband IoT
OPC UA	Open Platform Communications Unified Architecture
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
QoS	Quality of Service
SCP	Sensor Configurator Platform
SDTP	Sensor Data Transmission Protocol
TCP	Transmission Control Protocol
TLS	Transmission Layer Security
UDP	User Datagram Protocol
URL	Uniform Resource Locator
WUI	Web User Interface
XMPP	Extensible Messaging and Presence Protocol

1 Introduction

1.1 Background

Digital twin is a digital counterpart of a physical object, which accurately mirrors the current state of its corresponding physical twin. It offers numerous benefits throughout the product life cycle. Therefore, the concept of a digital twin has gained a lot of attention recently. In addition, it is developed by the world's largest companies such as Siemens (Boger & Rusk, 2017), and Gartner has chosen it three times in a row to its *Top 10 Strategic Technology Trends* list (Panetta, 2016, 2017, 2018b).

Despite a digital twin concept is constantly developed, there is a lack of real-world implementations of it. This is because a digital twin is a complex system of systems having numerous functionalities. This thesis focuses on the digital twin's functionality of representing the current status of the physical twin, which is enabled by data collection from the physical twin. The thesis narrows the gap between the concept of a digital twin and its implementation in two ways:

- By presenting communication methods suitable for sensor data transmission from a physical twin to a digital twin
- By introducing a platform for managing sensors remotely allowing this data transmission

This thesis has been written as part of DigiTwin-project, which aims to the realization of a digital twin concept by creating a digital twin of the overhead crane called Ilmatar. The crane is located at Aalto University Industrial Internet Campus (Figure 1) and it is used as an example of a product having a digital twin in this thesis. This thesis supports the DigiTwin-project by allowing data collection from the overhead crane with the developed platform for management and configuration of sensor nodes.

Figure 1. Ilmatar overhead crane located at Aalto University Industrial Internet Campus.

1.2 Objective

In order for a digital twin to mirror accurately the current state of its physical twin, measurement data from the physical twin has to be collected continuously. For that reason, numerous sensors have to be attached to it. The massive amount of data produced by these sensors is needed to be transmitted to the digital twin. The first objective of this thesis is to present the most suitable application layer protocols and communication technologies for this sensor data transmission.

The second objective is to enable sensor data transmission from a physical twin to a digital twin in practice. To fulfill this goal, a tool for management and configuration of sensor nodes is developed. The platform is required to support multiple sensor types and allow the addition of new sensor nodes to the physical twin effortlessly. Both objectives of this thesis ultimately aim at narrowing the gap between the concept of a digital twin and its realization.

1.3 Scope

This thesis focuses on data transmission from sensor nodes to a digital twin. The other communication needs of a digital twin such as communication between digital twins are identified, but not examined in more detail. The communication was limited to the sensor data transmission because it is the most important part of a communication of a digital twin: Without sensor data, a digital twin could not mirror the current state of its physical twin. The most suitable application layer protocols and communication technologies for the sensor data transmission are examined by a means of the literature research. The review of communication technologies focuses on wireless technologies, because with a large number of sensors needed to mirror the state of a physical twin, the wiring becomes challenging. However, if possible, wired communication should always be used over wireless communication as it is a more reliable option.

The tool for managing sensors is designed to support numerous sensor types. However, in this thesis, only I^2C bus sensors are considered. In addition to the platform, a new application layer protocol to allow higher continuous sample rates and a data server to mimic the data storage of a digital twin are implemented. However, the emphasis is on the development of the platform.

1.4 Structure of the thesis

In the next chapter, a literature review of the concept of a digital twin is provided as the term digital twin is relatively new and not yet established. Thereafter, the digital twin is defined in the context of this thesis and the data it needs to operate is presented. The third chapter examines the communication of a digital twin. Communication needs are identified, and the most suitable application layer protocols and communication technologies for data transmission from sensor nodes to the data server are presented. In addition, a short review of existing IoT platforms allowing sensor management is presented. In the fourth chapter, requirements for a platform enabling management of sensor nodes and their data transmission is introduced. The hardware and software used for creating the developed platform are also shortly described. The fifth chapter presents the Sensor configurator platform, the protocol developed for data transmission from sensor nodes to the data server, the implemented data server, and user tests of the Sensor configurator platform. The sixth chapter discusses the significance of the results, and finally, the conclusion of this thesis is presented in the seventh chapter.

2 Digital twin

In this chapter, the background and concept of a digital twin are presented. In the first section, the history and initial goals of predecessors of a digital twin concept are examined. The second section presents the definitions of a digital twin in the scientific literature and the third section introduces the definition of digital twin used in this thesis. Finally, the data needed and produced by a digital twin is presented in the fourth section.

2.1 Background

The term *digital twin* is fairly new and was first brought to the public by Shafto et al. (2010, 2012; Schroeder et al., 2016, p. 13) However, very similar ideas to the digital twin have already been developed at the beginning of the 2000s by, for example, Grieves (Grieves & Vickers, 2017, p. 93) and Främling et al. (2003). In this section, a few predecessors of a digital twin concept are presented. These concepts share some similar features to the current vision of a digital twin but can't yet be called digital twins.

Brussel et al. (1999) represent "holons", which are autonomous agents for Holonic manufacturing system (HMS). Holons can co-operate to achieve a common goal as well as react to disturbances and optimize the process. HMS consists of three basic building blocks: 1) *product holon*, which contains information about product itself such as up-to-date information on the product lifecycle and bill of materials, 2) *resource holon* used for resource allocation, which consists of physical part (resource) and information-processing part, 3) *order holon*, which is "an active entity responsible for performing the work correctly and on time."

Wong et al. (2002) introduce the concept of an intelligent product and examine its effects on the lifecycle of the product. They define an intelligent product as having at least some of the following characteristics:

1) Unique identity
2) Ability to communicate with its environment
3) Can retain or store data about itself
4) Can express its features, production requirements etc.
5) A capability of participating in or making decisions relevant to its own destiny

Software agents enable intelligent products to address the above-mentioned features 4 and 5. Wong et al. define software agent as "a distinct software process, which can reason independently, and can react to change induced upon it by other agents and its environment, and is able to cooperate with other agents". Figure 2 shows an example of the tagged jar sauce. The tag is used to link product through a local or remote network to information about itself as well as its software agent. (Wong et al., 2002)

Hribernik et al. (2005) use the above definition by Wong et al. (2002) to describe the properties of the Product Avatar concept. Each product has a digital counterpart called Avatar in a virtual reality. Avatar is capable of autonomous decision-making and is an individual object itself. A Product-Centric Approach (Hribernik et al., 2005, 2006) (Figure 3a) is proposed to manage product-related information in which the product itself manages and act as a link between the information relevant to itself. In the traditional approach (Figure 3b), information is stored by individual parties and therefore is not easily accessible. Access to data collected during the product lifecycle allows the optimization of for example operation, maintenance, and repair.

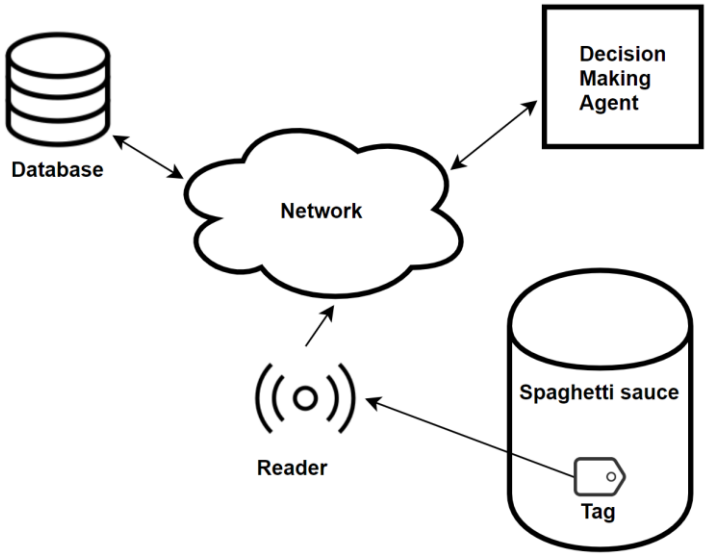


Figure 2. The intelligent product is identified with an RFID tag, after which it can be linked to the information about itself and its software agent. In a digital twin concept, there is a bi-directional communication between the physical and digital twin. Redrawn from (Wong et al., 2002, p. 2).

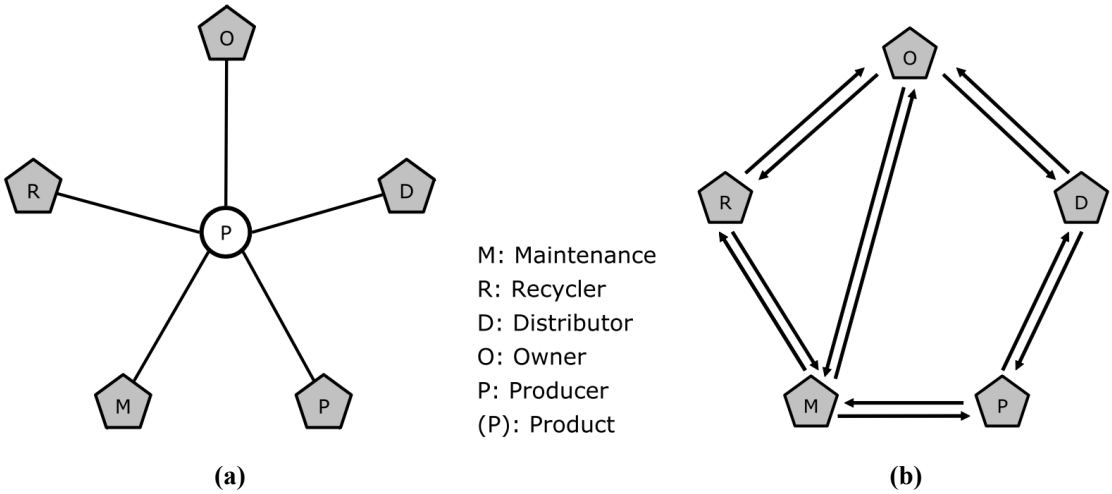


Figure 3. Relationships between actors in the Product Life-cycle with Product-Centric Approach (a) vs. traditional approach (b) (Hribernik et al., 2005, pp. 2–3).

Främling et al. (2003) propose an agent-based architecture to manage the information of a product during its whole lifecycle. Each product has a corresponding "virtual counterpart" called agent (Främling et al., 2003, p. 5), which is an autonomous software component capable of interacting with other agents (and possibly humans), react to changes in its environment and act towards a specific goal (Wooldridge & Jennings, 1995; Holmström et al., 2002, p. 41). The agent of a product can be accessed via Internet and it makes the information of the product accessible (Främling et al., 2003).

Grieves (2005) introduces the Mirrored Spaces Model (MSM), which consists of the real space, virtual space, and linkage between the spaces. Objects in the virtual space are linked to their physical counterparts in the real space and mirror their state. MSM enables the product lifecycle management by making the product data available throughout its lifecycle. MSM was first renamed as IMM (Information Mirroring Model) and later as Digital Twin (Grieves & Vickers, 2017, pp. 93–94). In his book, Grieves (2011) presents

the value of virtual products to the PLM (Product Lifecycle Management) and further develops the IMM concept (Grieves & Vickers, 2017, p. 93). Grieves is generally considered as the creator of the concept of a digital twin, even though Shafto et al. (2010) first presented the term digital twin.

Kiritsis et al. (2011) define an intelligent product as a "product system which contains sensing, memory, data processing and communication capabilities at various intelligence levels." The intelligence of a product is divided into four levels: a product at intelligence level 1 does not have any intelligence and product at level 4 is capable of decision-making and communication with its environment. Smart products enable data collection, which closes the PLM information loop. This allows manufacturers to get data from the actual use of the product and improve the maintenance operations, as the up-to-date status of the product is known. The smart products change the focus from the product type to the individual product.

The concept of Cyber-Physical System (CPS) is closely related to a digital twin as a digital twin can be seen as "the cyber part of a Cyber-Physical System" (Autiosalo, 2018, p. 243). Lee (2008, p. 363) describes CPSs as "integrations of computation with physical processes". In a CPS, sensor data is collected and analyzed to control the physical process (Alam & El Saddik, 2017, pp. 2050–2051). It can be seen from the Scopus database that the concept of CPS has emerged a few years earlier than a digital twin, and the amount of publications related to CPSs is twentyfold compared to digital twins. The Cyber-Physical Systems can be seen as another path leading to the development of a digital twin because CPS can use a digital twin to process the sensor data and control the physical system (Alam & El Saddik, 2017). Further examination of the concept of CPS and its similarities to the concept of a digital twin is out of the scope of this thesis.

As a conclusion, predecessors of a digital twin addressed the following issues:
1) Where to store the product data?
2) How to share the data among various stakeholders?
3) How to store and manage data related to product life-cycle management?
4) How to add intelligence to the product?
5) How can products communicate with each other?

The current vision of a digital twin also addresses these problems but expands the capabilities to the next level as the technology has considerably advanced since the beginning of the 21st century. It is noteworthy that the later concepts of a product agent such as one presented by Främling et al. (2013) are very similar to the current concept of the digital twin. Thus, instead of a new concept, a digital twin should be seen as a next step in the development of 'intelligent products'.

2.2 Concept

In this section, purposes and definitions of a digital twin in the scientific literature are examined. The purpose and definition are inseparable as the digital twin is often defined by its intended use.

The literature review was conducted by using the Scopus Database. The search phrase was "digital twin" and it was targeted to title, abstract and keywords. The release date of the publications was limited to years 2010-2018, as the term "digital twin" was used first time in 2010 by Shafto et al. (Schroeder et al., 2016). The date of the search was 5.7.2018. Only publications written in English, which had five or more citations, were considered.

However, some of the publications were not accessible and therefore could not be included in this thesis. In addition, some of the publications used in this literature review does not fulfill the requirement for the minimum amount of citations but were still considered as they were otherwise relevant, for example, cited by the other papers or recommended by colleagues.

The first and probably the best-known definition of a digital twin is by Shafto et al. (2010, 2012) in NASA's (National Aeronautics and Space Administration) roadmap. It says: "a digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin." In addition, Shafto et al. (2010) state a digital twin integrates sensor data, maintenance history, and fleet data. A digital twin contains essentially all available data from the whole lifecycle of a physical twin from manufacturing anomalies to the operational data. In addition to being capable of accurately mirroring the current state of its physical twin, they propose that a digital twin is used to run simulations to predict the future states of its corresponding physical twin.

The following applications for a digital twin are represented by Shafto et al. (2010):

1) Flying the mission beforehand. This enables examination of the effects of modifying the mission parameters and strategies to mitigate the consequences of unexpected failures during the flight. A digital twin can also predict the probability of mission success.
2) Mirroring the state of the physical twin during the mission, which enables continuously predicting the future states of a physical twin by running simulations.
3) Analyze the cause of anomaly during the flight.
4) Predicting the effects of modifications to mission parameters during the flight. This can be used to make the most informed decision if there is a need to change the parameters, for example, as a result of the failure of a single system.
5) "Certification of vehicles by simulation"

As can be seen, NASA's vision of a digital twin is mainly focused on improving the safety of the flights.

Tuegel et al. (2011) also examine a digital twin from aeronautics perspective. A digital twin is described by being "ultrarealistic in geometric detail, including manufacturing anomalies, and in material detail, including the statistical microstructure level". A digital twin is capable of acting as a virtual sensor interpolating data acquired from real sensors. Currently, there is a separate model for each type of physics such as computational fluid dynamics (CFD) model, the structural dynamics model (SDM), and the thermodynamic model to predict the structural life of aircraft. With a digital twin, these models could be integrated. By having a digital twin containing all information related to specific aircraft tail number including reliability estimates of all primary structural components, the maintenance can be optimized. (Tuegel et al., 2011)

In another publication by Tuegel (2012), a digital twin is presented as a cradle-to-grave ultra-realistic computational model of the as-built aircraft. A digital twin consists of multiple integrated submodels. These submodels use the best available physics, share information with each other and are updated during the lifecycle of an aircraft so that the accuracy of the models is improved. An Aircraft Digital Twin enables virtual testing of the design, health monitoring and forecasting the need for maintenance.

Glaessgen & Stargel (2012) emphasize that a digital twin represents an as-built version of the vehicle or system and includes information at the level of material microstructure. This information about the physical structure on a scale from "less than a micron to meters" is used to create "ultra high-fidelity physical models to predict the future states of the vehicle". A digital twin can perfectly mirror the state of its corresponding physical twin and use ultra-high fidelity simulations to predict the physical twin's possible future states. Glaessgen & Stargel claim that with a digital twin it is possible to abandon empirical and heuristic design rules, which result in heavy structures as well as uncertainties related to the actual reliability of the structure. In addition, they claim a digital twin will revolutionize certification as the vehicle can be tested virtually.

Smarslok, Culler & Mahadevan (2012) present USAF's (United States Air Force) vision of a digital twin in which a digital twin enables "condition-based fleet management by tail number through numerical simulation of the structural response to the same flight spectrum as experienced by the physical system." They take steps towards the actual implementation of a digital twin vision by creating a framework to assess the confidence in model predictions for the aerothermoelastic model. Without this assessment of confidence, a digital twin would not be able to make autonomous decisions regarding efficient simulations and risk mitigation.

Lee et al. (2013) expand the usage of digital twins from aeronautics to manufacturing systems. They describe a digital twin as a coupled model of the real machine, which "operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms as well as other available physical knowledge." A digital twin has knowledge of product design as well as the current condition of the physical machine. In addition, in their vision a digital twin eases the access to the information about the physical product.

Cerrone et al. (2014) further motivate the need for a digital twin concept by providing a use case, in which the path of the crack is predicted with the finite element model. To predict the path, the as-manufactured geometry of the specimen is required. Therefore, they emphasize a digital twin's ability to store information about the as-manufactured properties of the product.

Grieves (2014) presents a digital twin concept's benefits to manufacturing. He describes a digital twin as a "virtual, digital equivalent to a physical product", which is "virtually indistinguishable" of its physical counterpart. He divides the concept of a digital twin into three parts: physical products, virtual products, and the connections and information, which links these digital and physical products together. For this linkage, he proposes Unified Repository (UR), which includes the design data and data collected from the physical product. For example, when a product is manufactured, the factory's MES (Manufacturing Execution System) pushes the information of the as-manufactured characteristics of a product to UR. The information of the manufacturing process could also be sent to factory simulation, which enables almost real-time or real-time visualization of the factory state. In addition, this information allows a comparison between the desired products and the actual products being manufactured.

Even though Bazilevs et al. (2015) have "digital twin" in their article's keywords, they use the term Dynamic data-driven application system (DDDAS) instead of a digital twin. However, this DDDAS is similar to the digital twin concept and is defined as a "framework in which sensor and measurement data collected for a given physical system are

used to dynamically update a computational model of that system." The major difference between a digital twin and DDDAS is that in the DDDAS the structural model, instead of being an exact representation, is only a "fairly complete" representation of the physical structural system. In the article, DDDAS is used to improve the predictive power of the introduced framework for fatigue-damage modeling.

Ríos et al. (2015) compare the digital twin concept and the product avatar concept. The concepts are created from the different point of views and for different purposes, but address the same high-level issue of storing the data and information from the whole lifecycle of the product. They also identify several expected benefits of a digital counterpart such as the possibility to create intelligent services and accessibility to product information among various stakeholders through a product's lifecycle. A digital twin utilizes various interoperable models to represent the physical counterpart during its life cycle.

Rosen et al. (2015) state a digital twin is "the next wave in modeling, simulation and optimization technology" (Figure 4). Simulations should not be used only in the design phase, but throughout lifecycle supporting also the operation of the product. A digital twin is a necessary tool to create autonomous manufacturing system. It holds the information about the current state of the environment and the process, which is needed to optimize the system and to run forward simulations. These forward simulations are then used to support action planning of the autonomous system.

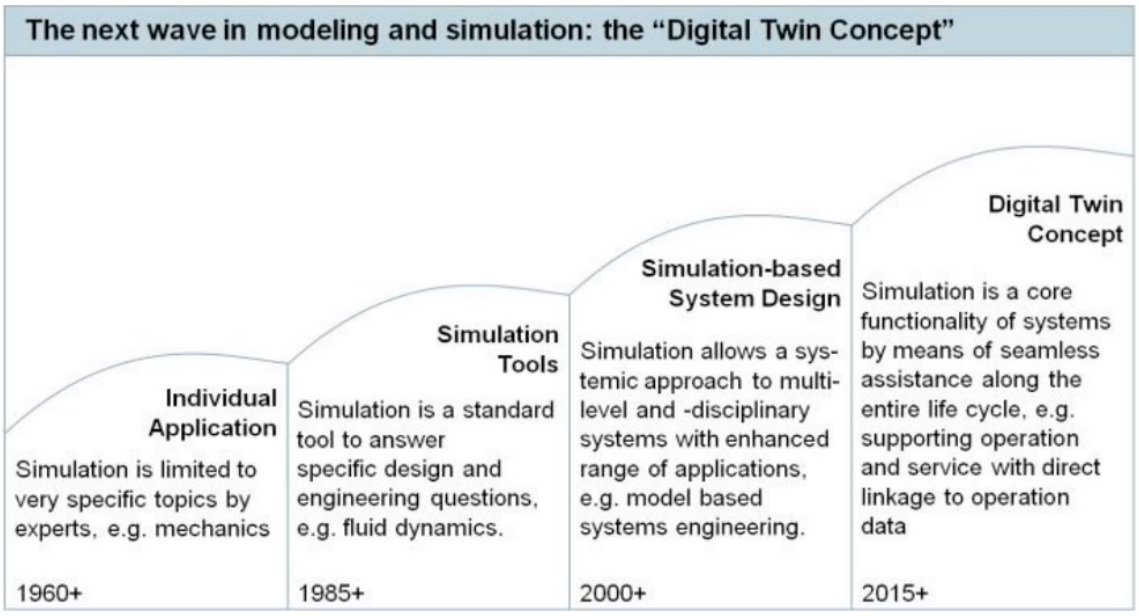


Figure 4. The Digital Twin concept is the next wave in modeling and simulation (Rosen et al., 2015, p. 568).

Gabor et al. (2016) describe a digital twin as an ultra-high fidelity simulation. A digital twin integrates previously separate structural models, which allows the system to be simulated as a whole. A digital twin has knowledge of all systems of its type and uses the information collected from those systems to improve the accuracy of simulations. If simulations can be run fast enough, the future behavior of the system can be predicted. Gabor et al. also claim that a digital twin can be used as a tool for testing as it has the ability to provide test cases. In addition, its ability to mirror the physical world enables to acquire virtual sensor readings and a software engineer to use virtual and physical components interchangeably.

Weyer et al. (2016) examine a digital twin from Cyber-Physical Production Systems (CPPS) perspective. With CPPS the production is more scalable and flexible, all phases of production are quickened, and (re-)engineering tasks previously performed sequentially can be performed simultaneously (Figure 5). Simulations are an essential part of CPPS as they can predict the system behavior and performance under changes supporting the decision-making. Simulations require an exact state of the system and therefore each physical component has a digital counterpart, which is used to store this information. A digital twin uses this information to "monitor, adjust and optimize real processes, anticipate failures and increase efficiency."

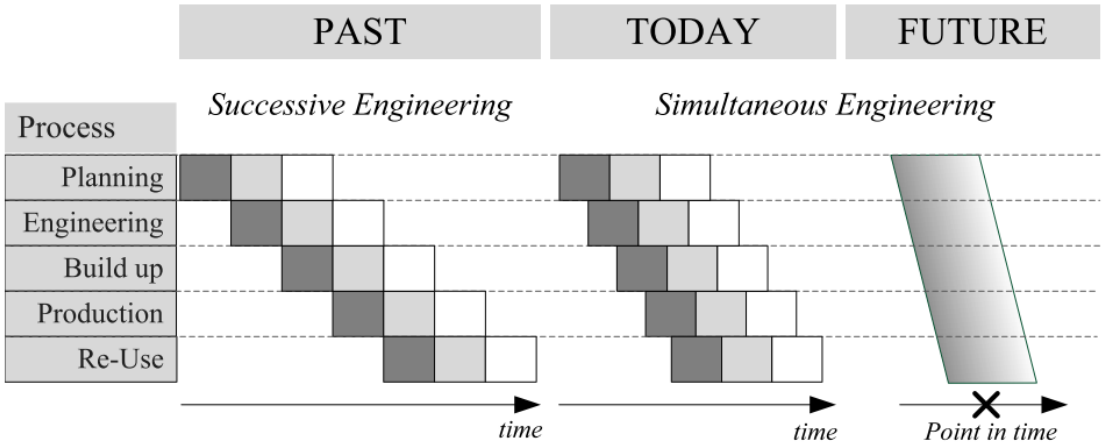


Figure 5. Cyber-Physical Production System allows previously sequentially performed tasks to be performed simultaneously. Colored squares are used to describe a single (re-)engineering step in the manufacturing system. (Weyer et al., 2016, p. 98)

Schroeder et al. (2016) see a digital twin as a virtual representation of a real product or as a cyber representation of a Cyber-Physical System (CPS), which contains all the information and knowledge of a physical product from its whole lifecycle. They use the term "Big Data" along with digital twin to describe the problem of managing the huge amount of data produced in all phases of a product's lifecycle. In their article, high-level data models for easy data exchange between systems is implemented with AutomationML.

Boschert & Rosen (2016) examine a digital twin's possibilities from a simulation point of view. A digital twin is described as "a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all—the current and subsequent— lifecycle phases." It acts as a link between separate systems such as PLM (Product lifecycle management), PDM (Product data management) and SCADA (Supervisory Control and Data Acquisition) storing product information and makes the data and set of various fidelity simulation models available. Boschert & Rosen state a digital twin can be seen as a part of the physical product, which helps the operation of a product via simulations throughout the product lifecycle. In the system integration testing, physical components can be replaced with virtual ones to allow testing even if the physical components aren't yet available.

Schluse & Rossmann (2016) combine a digital twin and virtual testbeds and call the result as an experimentable digital twin. This experimentable digital twin is used to improve the development process and operation of products by simulations. Figure 6 shows various dimensions of simulations and presents a paradigm change from simulation-centric to

digital twin centric. Digital twins are described as "virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services."

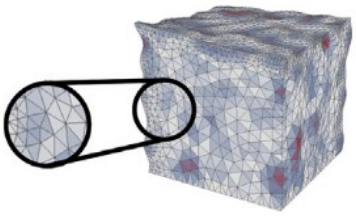
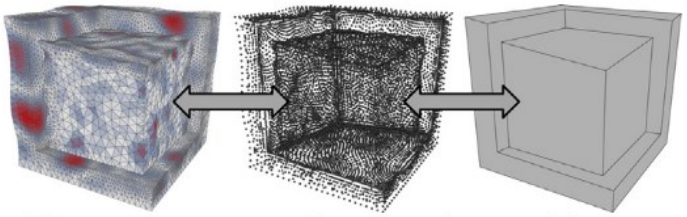
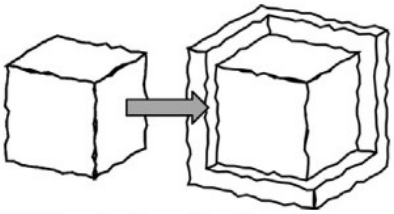
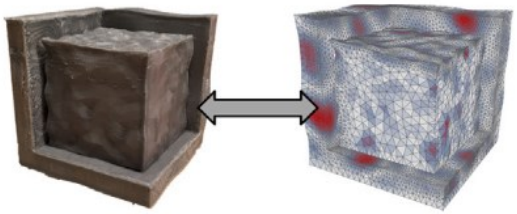
Figure 6. Various aspects of simulations (Schluse & Rossmann, 2016, p. 1).

A digital twin is used to predict the values of process variables to create robust components in additive manufacturing. The use of a digital twin reduces the need for time-consuming and expensive, "try-and-error", experiments. (DebRoy et al., 2017; Knapp et al., 2017) DebRoy et al. (2017) identify the building blocks needed to create a digital twin for additive manufacturing and Knapp et al. (2017) develop and experimentally verify a model to predict the values of process variables. A digital twin is "a digital replica of additive manufacturing hardware", which, along with integrated models of for example temperature and microstructure, is used for calculating the needed process variables (DebRoy et al., 2017).

Schleich et al. (2017) summarize the vision of a digital twin as follows: "a bi-directional relation between a physical artefact and the set of its virtual models." The distinct simulation models of a digital twin evolve during the lifecycle of the product from simple models to more complex ones. A digital twin helps to assess the consequences of design

decisions and improve the efficiency of manufacturing. Schleich et al. also introduce a novel reference model for a digital twin in design and production engineering. Its properties such as scalability, interoperability, expansibility, and fidelity are presented in Table 1.

Table 1. The properties of a reference model for a digital twin (Schleich et al., 2017, p. 143).

Scalability	Ability to provide an insight at different scales (from fine details to large systems). 
Interoperability	Ability to convert, to combine, and to establish equivalence between different model representations. 
Expansibility	Ability to integrate, to add, or to replace models. 
Fidelity	Ability to describe the closeness to the physical product. 

Uhlemann, Lehmann & Steinhilper (2017a) propose a concept for the implementation of a digital twin of the Cyber-Physical Production System for small and medium-sized enterprises (SME). They present a concept of a data acquisition system for tracking motion data, employees' activity, and use and position of machines. The system is based on sensors and machine vision and fits for SME's needs. A digital twin is described as a prerequisite for CPPS, which allows data analysis, predictions, and control of the production process. Uhlemann et al. (2017b) also introduce a concept of a learning environment to demonstrate the benefits of the digital twin concept, real-time data acquisition, and linked simulation.

Alam & El Saddik (2017) present a digital twin reference model for the Cloud-Based Cyber-Physical Systems (C2PS). They define a digital twin "an exact copy of the physical system that truely represent all of its functionalities". Each physical product has its own digital twin, which is deployed in a cloud. Digital twins are located at the cyber layer of

a cyber physical system and enable monitoring, diagnostics, and predictions of a physical counterpart as well as offers real-time services to the application layer of the CPS. The properties and functionalities of products are enhanced with their digital twin. A telematics-based driving assistance application is developed to demonstrate the C2PS. In this application, real-time processing is performed in the physical layer of the system and more resource intensive calculations are executed in the cloud.

Negri, Fumagalli & Macchi (2017) analyze the definition of a digital twin in the scientific literature and its role in Industry 4.0. Their definition of a digital twin is following: "the virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field." They found that the definition of a digital twin is not unanimous in the scientific literature. In addition, they found various uses of a digital twin such as:

- Health analysis
- Monitoring the system
- Maintenance optimization
- Mirroring the physical twin
- Predicting the system behavior
- Optimization of the system operation

Negri et al. (2017) also emphasize that the first publications in Scopus database, from years 2012-2013, are from the same *53rd/54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference,* and the number of publications started to rise in the year 2015. In addition, they note that most of the publications are conference proceedings indicating that the scientific literature of a digital twin is at its infancy.

Tao et al. (2018) present a digital twin as an effective way of managing and handling data through all phases of the product lifecycle (Figure 7). They present the following properties of a digital twin:

1) Real-time mirroring of the physical system.
2) Connecting data from all phases of the product lifecycle.
3) Continuous updating of virtual models.

A digital twin is used to improve the design of the product by for example offering data from previous generations and simulations. In the manufacturing phase, a digital twin concept allows resource management, monitoring, and optimization of the process. In the operation phase, a digital twin can offer the following services (Figure 8):

1) Real-time monitoring of a product state
2) Energy consumption analysis and prediction
3) User management and behavior analysis
4) Guidance to the operation of the product
5) Optimization of the system operation
6) Analysis and prediction of failures
7) Maintenance optimization
8) Maintenance operations can be trained by first performing them virtually
9) The operator of the product can train the use of the product virtually

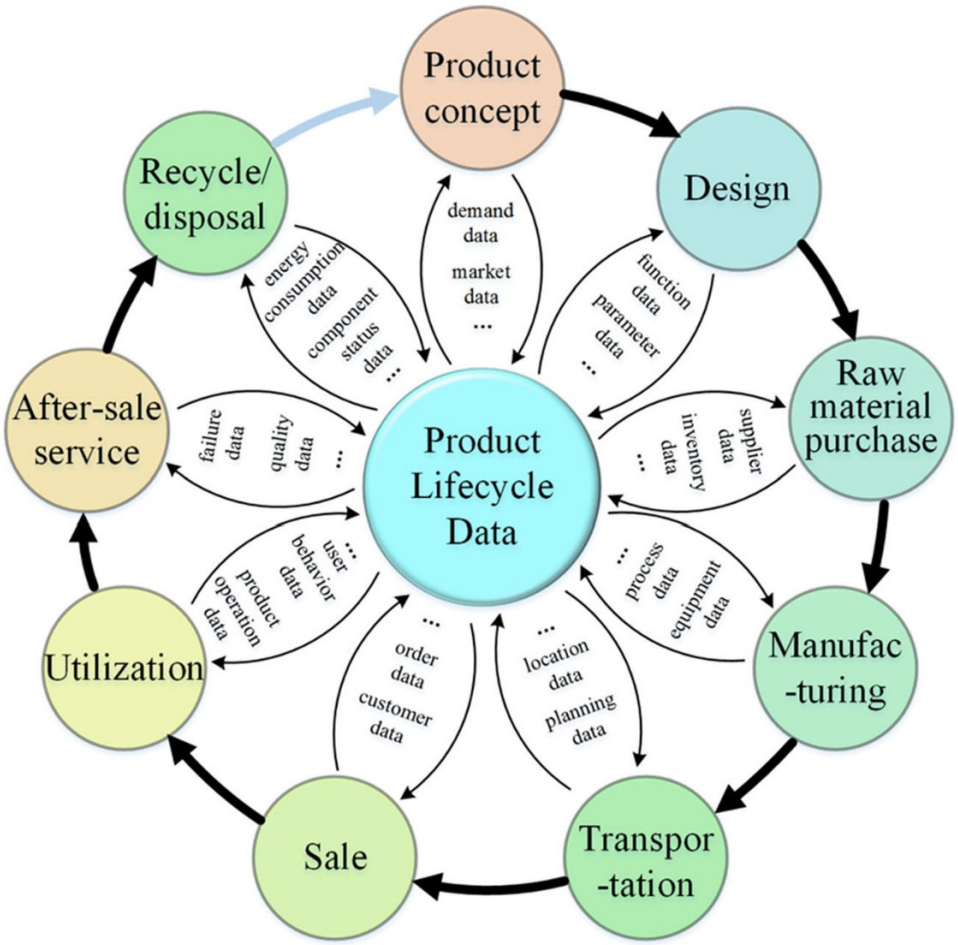


Figure 7. The phases of the product lifecycle and related data (Tao et al., 2018, p. 3565).

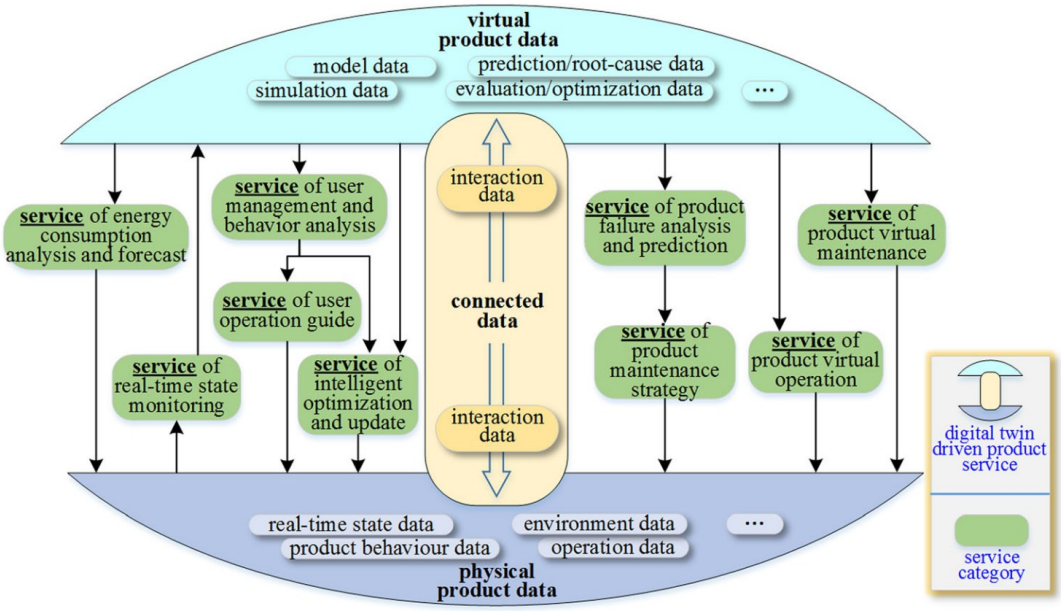


Figure 8. Services enabled by a digital twin (Tao et al., 2018, p. 3573).

Table 2 presents the definitions of a digital twin found in the scientific literature. It can be noted that the definition of a digital twin is not yet completely settled. However, the definition presented by Shafto et al. (2010) seems to be the most used definition of a digital twin. There are also various alternative definitions of a digital twin outside the

scientific literature by industry (Schleich et al., 2017). For example, Siemens defines a digital twin as "an integrated set of digital replicas or models" (Boger & Rusk, 2017) which are updated continuously to reflect changes to the physical counterpart (Maurer, 2017). This digital twin enables closed-loop of feedback, performance prediction and optimization, and condition-based maintenance (Boger & Rusk, 2017; Maurer, 2017).

The concept of a digital twin has also been researched for a few years at Aalto University. Autiosalo (2018, p. 243) defines a digital twin as "the cyber part of a Cyber-Physical System." Laaki et al. (2019) emphasize the role of a digital twin as an enabler of the communication with the physical twin and its property of making all the data of the physical twin located in "various data stores accessible via a single interface". They also examined the requirements for communication of a digital twin in a mission-critical application using a prototype of a remote surgery system. In addition, several digital twin related theses have been written in Aalto University. For example, Lönnqvist (2018) examines how an engineering company deployment of a digital twin, and Lagus (2018) presents the requirements for a digital twin's information security.

A digital twin is sometimes described as being "ultra-realistic" (Tuegel et al., 2011; Tuegel, 2012). Indeed, there are not yet many implementations of a digital twin. For example, the following challenges of the realization of a digital twin can be found in the scientific literature:

- A large database needed is difficult to maintain and requires high output (Tuegel et al., 2011, p. 10)
- Uncertainty quantification of the simulation results (Tuegel et al., 2011, pp. 9–10; Schleich et al., 2017, p. 142)
- Lack of high-quality models (Schleich et al., 2017, p. 142)
- Information sharing between distinct models (Tuegel, 2012)
- Information is spread around the organization (Grieves & Vickers, 2017, p. 108)
- The boundaries between fields of engineering (Grieves & Vickers, 2017, p. 108)
- Understanding the physical world (Grieves & Vickers, 2017, p. 108)
- Collection and processing of large data sets (Schleich et al., 2017, p. 142)
- The amount of data needed to present all information of the physical product is too large and data is both unstructured and diverse (Boschert & Rosen, 2016, p. 66)
- The need for high computational power (Tuegel et al., 2011; Grieves & Vickers, 2017, p. 109)

Table 2. Definitions of the digital twin in the scientific literature.

Reference	Definition	Use	Field
Shafto et al. (2010)	"An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin"	Simulating the flight beforehand, mirroring the state of physical twin, analyze the cause of anomaly, predictions	Aeronautics
Tuegel et al. (2011)	"Ultrahigh fidelity model of an individual aircraft", which is "ultrarealistic in geometric detail, including manufacturing anomalies, and in material detail, including the statistical microstructure level"	Act as a virtual sensor, integrating models, storing information, maintenance optimization	Aeronautics

Tuegel (2012)	A tail number specific cradle-to-grave ultra-realistic as-built and maintained computational model of an individual aircraft. “An integrated collection of submodels.”	Estimation the remaining lifetime, managing the information about the configuration, maintenance optimization, virtual testing	Aeronautics
Glaessgen & Stargel (2012)	“An integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc. to mirror the life of its corresponding flying twin.”	Certification, fleet management, monitoring, and mitigating anomalous events, forecast the health of the vehicle or system	Aeronautics
Smarslok et al. (2012)	Enables “condition-based fleet management by tail number through numerical simulation of the structural response to the same flight spectrum as experienced by the physical system”	“Condition-based fleet management by tail number”, life-prediction, simulations, risk mitigation	Aeronautics
Lee et al. (2013)	“The coupled model”… “of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms as well as other available physical knowledge.”	“Integrate, manage and analyze machinery or process data during different stages of machine life cycle” to allow health condition monitoring	Manufacturing
Cerrone et al. (2014)	Not explicitly defined	Predicting the crack path by modeling as-manufactured geometry	General/ aeronautics
Grieves (2014)	“Digital equivalent to a physical product”	Real-time visualization of factory state. Comparing the desired result and actual result	Manufacturing
Bazilevs et al. (2015)	“A high-fidelity structural model that incorporates fatigue damage and presents a fairly complete digital counterpart of the actual structural system of interest”	Fatigue damage prediction	General
Rios et al. (2015)	“‘As-built’ digital structure of a physical product”	“Defining, simulating, predicting, optimizing and verifying the product along with its life lifecycle”	General/ aeronautics
Rosen et al. (2015)	“Realistic models of the current state of the process” and system “behavior in interaction with its environment in the real world”	“Represents the full environment and process state.” Forward simulations to support the decision-making of an autonomous system	Manufacturing

Gabor et al. (2016)	An ultra-high fidelity simulation integrating previously separated structural models	Support the design process of the system. Simulation of the system as a whole, predict system behavior	General/ manufacturing
Weyer et al. (2016)	Not explicitly defined	"Monitor, adjust and optimize real processes, anticipate failures and increase efficiency"	Manufacturing/Automotive (production)
Schroeder et al. (2016)	"A virtual representation of the real product." "Cyber presentation in the context of the Cyber Physical Systems."	"Monitor and control of the physical entity"	Manufacturing/product services
Boschert & Rosen (2016)	"A comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all—the current and subsequent— lifecycle phases."	Information of system is available throughout the product lifecycle, possibility to use data collected to improve future products	General
Schluse & Rossman n (2016)	"Virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services."	Improving the development process and operation of the product by simulations	Manufacturing/robotics
DebRoy et al. (2017)	"A digital replica of additive manufacturing hardware", which integrates models for temperature, microstructure and properties, and residual stresses and distortion	"Minimizing expensive trial and error optimization", "shortening the path for product qualification", and "reducing/alleviating defects"	Additive manufacturing
Knapp et al. (2017)	Not explicitly defined	"Minimize the time consuming and expensive empirical tests to evaluate the effects of the process variables"	Additive manufacturing
Schleich et al. (2017)	"Sophisticated virtual product model" with "a bi-directional relation between a physical artefact and the set of its virtual models"	"Enables the efficient execution of product design, manufacturing, servicing, and various other activities throughout the product life-cycle"	Design/production engineering
Uhlemann et al. (2017a)	Not explicitly defined	"Near real-time production control applications." Optimization of the process	Manufacturing in SME

Uhlemann et al. (2017b)	Not explicitly defined	Enhance transparency, improve control and optimization of the process by offering near real-time data	Learning
Alam & El Saddik (2017)	"An exact cyber copy of a physical system that truly represents all of its functionalities."	Connect physical things to the application layer of CPS. "Monitoring, diagnostics, prognostics"	Smart City/ vehicles
Negri et al. (2017)	"Virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field"	Health analysis, monitoring the system, maintenance optimization, mirroring the physical twin, predicting the system behavior, optimization of the system operation	Literature review
Tao et al. (2018)	"An integrated multi-physics, multi-scale, and probabilistic simulation of a complex product that uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin."	A holistic solution for PLM data, improving the design, manufacturing, and operation of a product, simulations, predictions, virtual training	Design/manufacturing/operation of product (PLM)

The general definition of a digital twin is difficult to establish because the requirements and needs for a digital twin depends on the field. The ambiguity of the concept of a digital twin causes the need to define it separately in each study. Therefore, in the next section, a digital twin is defined in the context of this thesis.

2.3 Digital twin in this thesis

The previous section shows that the definitions of digital twin are wide-ranging, vary in different fields and are sometimes even contradictory. Therefore, it is necessary to present a definition of a digital twin in the context of this thesis. The following section describes the properties and intended use of a digital twin of an overhead crane.

In the context of this thesis, a digital twin is defined as follows: A set of linked systems enabling accurate examination of the historical data, current state, and possible future states of the physical twin. The architecture of a digital twin is shown in Figure 9 in which each of the 'boxes' represents features of a digital twin. These features are implemented with one or more systems. For example, data storage can be a single data server or consists of various types of data storages. Next, each of these features are described in more detail:

1) Visualization tools. These tools enable the visualization of the data collected. The visualization of the product might also include a complete, realistic 3D-model of the product, which allows the operator or maintainer to practice the use of the product beforehand (Tao et al., 2018). In the future, AR (augmented reality) and VR (virtual reality) technologies offer further possibilities to virtual training and guidance to the use of a product.
2) Data analysis tools. A digital twin collects and stores a vast amount of data throughout the product lifecycle. This data can then be analyzed to optimize the

operation of the product. Data analysis can also show errors in the product and simulation models because the control parameters and predicted behavior can be compared to the actual behavior of the product. In addition, the difference between the intended use and the actual use of the product can be recognized. This information can be used to improve the design of the product.

3) Simulation models. A digital twin can be used to predict the product future states and the structural health of the product (Tuegel et al., 2011; Glaessgen & Stargel, 2012). In addition, the effects of changing the configuration parameters of the product can be examined with simulations in the design phase as well as in the operational phase of the product. A digital twin might have multiple integrated simulation models, which use the best available physics-models. (Shafto et al., 2010)
4) Product models. These models can be used by the simulation models and visualization tools. The models are updated throughout the product lifecycle and accurately mirror the current state of the physical product. Product models can be, for example, CAD models.
5) Data storage. The massive amount of various and unstructured data is stored during the product lifecycle (Boschert & Rosen, 2016). The data storage system is responsible for storing this data and ensuring its availability and durability. Data storage might consist of several databases (for example NoSQL database for storing unstructured data and real-time database for data that needs to be available at a certain time limit) and a file system.
6) Decision-making. A digital twin should be able to make decisions autonomously. It can self-optimize its operation and in case of an unexpected situation, react faster than a human operator.
7) Link. As a digital twin consists of multiple systems, it is necessary to link these to enable cooperation. A link knows the location (such as URL) of all systems, which might be physically located all around the world, and takes care of the information exchange between them. For example, if data analysis tools need the measurement data, the link provides the location of the data storage. For all components, it is only necessary to know the location of the link.
8) User interface. A digital twin provides a user interface for easy configuration and monitoring of the product. In addition, visualization tools can be accessed through the user interface.

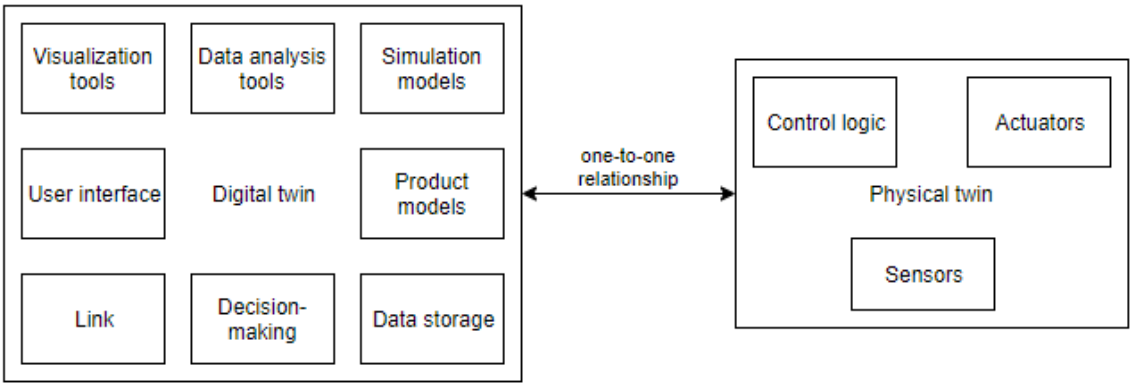


Figure 9. A digital twin is a set of systems, which has one-to-one relationship with a physical counterpart.

A digital twin improves the properties of a physical product (Alam & El Saddik, 2017) and might be deeply integrated with the physical product. Even so tightly that the physical product is not functional without its digital counterpart. For each physical product, there

exists only one digital twin: there is a one-to-one relationship between the physical and digital counterparts (Ríos et al., 2015, pp. 661–662; Alam & El Saddik, 2017, p. 2053). However, a complex product might consist of multiple components each of those having their own corresponding digital twin. Therefore, a digital twin might consist of multiple digital twins.

A physical counterpart contains actuators, a myriad of sensors to provide enough information for a digital twin to know exactly the current status of the physical product, and control logic (Figure 9). If a real-time control of the product is needed, control logic needs to be located close to the physical product. Usually, it should be embedded in the physical product, but edge computing can also be utilized. A digital twin updates the control logic of the physical product or can even control it directly if the requirement for latency is not very strict.

The above definition of a digital twin and its functionalities are also valid for the overhead crane used as an example in this thesis. Below, the specific use cases for a digital twin of an overhead crane are presented for both the manufacturer and the user of the crane. For the manufacturer:

- Verify the design of the overhead cranes in the real environment
- Optimization of the maintenance by knowing historical loads of an individual crane
- Providing customized inspection lists and the information of the as-maintained state of the crane to the maintainer
- Fleet data provides information about individual components quality

For the user of the crane:

- Provide information to customers external systems such as MES
- Data about the use of a crane
- Optimizing the routes of the overhead crane
- Visualizations of the crane can ease the use of the crane and allow virtual training
- Advanced features such as anti-sway control of the crane
- The crane can communicate with its environment and adjust its operation. For example, if there is no rush on the factory, the crane can drive slower to save wearable parts.

The above use cases are used as guidelines to derive the data needed by a digital twin presented in the following section and to choose the use cases for the assessment of application protocols and communication technologies.

2.4 Data contained in a digital twin

To identify the communication needs of a digital twin, it is necessary to examine what types of data it contains and what type of data is needed to be transmitted. In this section, the data a digital twin contains is first presented at a general level, and thereafter from the overhead crane point of view.

The generic digital twin can be described as containing the following data:

- Simulation models, which might be stored to an external system. If a simulation is needed to be performed the model can be fetched from the external system or the whole simulation can be run on that system. However, in some cases, forward simulations are continuously run, in which case the simulations should be performed close to other parts of a digital twin and physical twin to reduce delays.
- Product models. These might also be stored to an external system. Product models are updated continuously to mirror the state of the physical product: they include

the maintenance data and changed components as well as information about the wear of the material of the product.

- Design parameters and data. This data can be stored to a manufacturer's system and might not be accessible by users of the product. The existence of the design data allows improving the later versions of the product. The design data can also be compared to the data collected from the field to compare if the product is used as intended. Thereafter, the design parameters can be modified to better reflect the real use of the product.
- Measurement data from various sensors. The physical quantities measured as well as the requirements for data quality and measurement rates are highly dependent on the type of product. In addition, if the product uses the measurement data to control itself, low latency is needed.
- Miscellaneous data. There is a substantial amount of miscellaneous data such as instructions related to every product. Miscellaneous data is unstructured and diverse as it can be almost any kind of data such as documents or videos.

However, as the products having a digital twin are different from each other, also the data contained in their digital twins is diverse.

Because the digital twin of an overhead crane is used as an example in this thesis, the data it contains is presented in more detail. This data can be derived from the list above and from the use cases for the digital twin of an overhead crane presented in the previous section. The data the digital twin of an overhead crane contains includes:

- Simulation models. These allow calculating loads of an overhead crane using FEM analysis. The simulation results can be combined with the measurement data, which enables improving the model accuracy. Simulation models could also be utilized by, for example, anti-sway control of the crane. In addition, the wear of the machine could be predicted by running simulations based on the measurement data.
- Product models. These contain the as-maintained structure of the crane including all modifications to the standard configuration and replaced parts. The product models also include visualizations of the crane. These visualizations can be used to assist inspections and train the crane operators.
- Design data. The design data includes, for example, the environment and expected use of the crane. In addition, it includes the maximum loads and safety factors. The design parameters can be compared to the actual usage of the crane to see if they have been selected correctly. The parameters can then be modified to improve the efficiency of future generations of cranes.
- Measurement data. In order for a digital twin to accurately mirror the current state of the overhead crane, a myriad of sensors, which produce a vast amount of data, are needed to be attached to the crane. Sensors could measure, for example, the weight of the payload, the vibrations in wheels, the strain of the bridge, and the location of the hook. In addition, machine vision could be used to visual inspection of the crane. The type of data defines how often it is sent to the data storage of the digital twin. For example, if the location of the hook is used for controlling the movement of the crane, it should be transferred nearly real-time. Whereas, if the temperature of the environment is monitored, it is likely to be enough to send it e.g. every 10 minutes to the data storage. Data can also be processed before transmitting it to save storage space. For example, if the vibration in the wheels stays at the same level, it may be sufficient to send only the average level and characteristics of vibration instead of the whole measured data. However, data processing can hide the emerging underlying phenomenon. The automation data,

which includes information used for controlling the machine, can also be included in the measurement data. This information can usually be fetched from the PLC (Programmable logic controller) system of the machine.
- Miscellaneous data. This includes for example instructions for the maintenance and operation, the log of crane users, and the description of the environment in which the crane is used.

A digital twin can act as a common data storing platform and allows the sharing of the data between the various actors throughout the product lifecycle (Hribernik et al., 2005). In addition, it can be linked to external IT systems making the data from those systems available (Boschert & Rosen, 2016, pp. 66–67). When the digital twin itself also consists of multiple systems communicating with each other, a significant amount of data is needed to be transmitted in the context of a digital twin. For example, in order to optimize its operation, the following phases, shown in Figure 10, are performed:

1) Sensors collect data about the operation of the product and store the data in data storage.
2) The measurement data is fetched from data storage to data analysis tools.
3) The results of data analysis are sent to the decision-making part of the digital twin, which makes the decision if the control logic should be updated.
4) Control logic is updated.

In addition, decision-making could use, for example, the design data to asses if the machine operates as expected or requirements an operator of the machine has set for its operation.

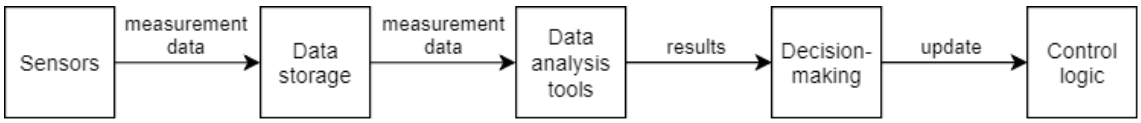


Figure 10. Self-optimization of the machine operation.

This chapter presented the background of a digital twin concept and examined its definition in the scientific literature. In addition, the definition of a digital twin in the context of this thesis was introduced and the data a digital twin contains was described in general level and in the case of an overhead crane. In the following chapter, the communication needs of a digital twin are identified based on this definition and the data a digital twin contains described in this section. In addition, the use cases for the communication of a digital twin are derived from the use cases for a digital twin of an overhead crane presented in the previous section. Finally, the most suitable application layer protocols and communication technologies for the sensor data transmission are assessed.

3 Communication

In this chapter, the communication of a digital twin is examined. First, the communication needs of a digital twin are identified. Thereafter, use cases for assessing the application protocols and communication technologies are presented. Section 3.3 shortly presents the layered architecture of the internet and the widely used OSI-model. In section 3.4, the most commonly used application layer protocols are examined, and, in section 3.5, most relevant wireless communication technologies in the context of a digital twin and IoT communication are introduced. Finally, a short review of IoT platforms, which enable data collection and sensor management, is presented.

3.1 Communication needs

A digital twin contains a vast amount of diverse data described in section 2.4. This data is constantly updated and exchanged between systems a digital twin consists of or external systems and a digital twin. The communication needs of a digital twin can be divided into the following categories (as illustrated in Figure 11):

1) communication between the subsystems of a digital twin
2) communication between digital twins
3) communication between a digital twin and its corresponding physical counterpart
4) communication between a digital twin and external systems
5) communication between a digital twin and its environment

Next, each of these forms of communication is described in more detail.

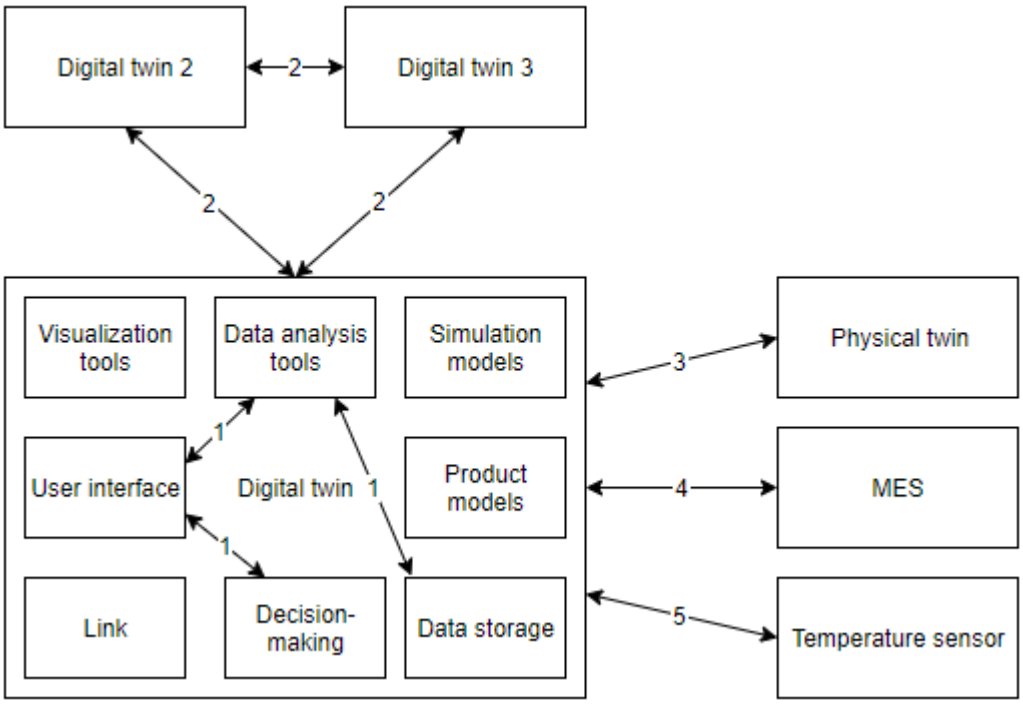


Figure 11. Communication of a digital twin can be divided into five categories.

Communication between the systems a digital twin consists of. A digital twin consists of several systems: each part of a digital twin shown in Figure 9 can be described as a system or even as consisting of multiple systems. These systems constantly interact with each other, for example, simulations use data from data storage and simulation results are used by decision-making to optimize the operation of the machine. The interoperability between systems requires standardized interfaces for communication.

Communication between digital twins. A digital twin might consist of several other digital twins. For example, each part (at least the larger ones) of an overhead crane have their own digital twins. The communication between digital twins can be divided into two categories: communication between digital twins a larger digital twin consists of, for example, between trolley and bridge of an overhead crane, and communication between digital twin and other machines' digital twins, for example, between digital twins of overhead cranes located at the same factory hall. By communicating with each other, digital twins can, for example, share information about their environment or about their statuses and future actions. The communication between digital twins of machines allows co-operation of the physical machines.

Communication between a digital twin and its physical twin. The communication between a digital twin and its physical counterpart can be divided into two categories: Data transmission from the physical twin to the digital twin, which includes sensor data and status data, and data transmission from a digital twin to physical twin, which includes remote control commands and software updates. This thesis focuses on the former category, as the data collection from the physical twin is the key enabler for the realization of a digital twin. In addition, a digital twin needs to know the status of the physical counterpart by its definition.

Communication between a digital twin and external systems. External systems can act as data storage, offer computational power or enable simulations. They also include, for example, MES to which digital twins used in production can push the manufacturing data. An external system should offer a standardized interface a digital twin can use for communication. Therefore, communication between external systems and systems a digital twin of are not differing from each other. Actually, the boundary between external systems and systems a digital twin consists of is quite fluid as both can be located at the cloud and offer similar services. The major distinguishing factor is that external systems are managed by an external party instead of the owner of the digital twin.

Communication between a digital twin and its environment. This includes monitoring of physical twin's environment and informing the environment about the status of the physical twin. Monitoring can be performed using physical twin's sensors or external sensor nodes. Informing the environment about the status of the physical twin increases safety and allows co-operation with the environment. If the external sensor nodes have digital twins and each (significant) part of the environment has their own digital twin, communication can be reduced to communication between digital twins.

This thesis focuses on the communication between a digital twin and its physical twin and, more precisely, on the sensor data transmission from physical twin to the digital twin. Sensor data transmission was selected for further examination as a digital twin is not a digital twin by a definition if it does not have knowledge of the current status of the physical twin. The measurement data from sensors is used to continuously update the digital twin so that it can have this knowledge of the current status. The following section presents the use cases considered in the assessment of the most suitable application layer protocols and communication technologies for the sensor data transmission later in this chapter.

3.2 Use cases

In this thesis, the focus is on the measurement data collected by sensors attached to the physical twin, that is, communication between the physical and the digital twin. Sensor

nodes attached to a physical twin should be wireless because wiring becomes challenging if there is an extensive number of sensor nodes. A sensor node is an IoT device, which contains sensor(s) and a microcontroller capable of sending data wirelessly. The applications of the IoT devices can be divided into the following categories (Qin et al., 2014, pp. 1–2):

- Real-time point-to-point applications, in which the status of the device needs to be transmitted reliably with low latency
- Monitoring applications collecting data periodically
- Data exchange between objects such as vehicles

This thesis covers the first two categories as the sensor data transmission from a physical twin to a digital twin is examined. Two more specific use cases related to the overhead crane are identified:

1) Sensor data is used to control the location of the hook in real-time
2) Sensor data is used to monitor the stress of the bridge

In the first case, the most important requirement for communication is low latency. In addition, high reliability and security are crucial factors. For example, if the connection is broken, the crane can't operate, or if incorrect measurement data is received, the crane might operate incorrectly or even dangerously. The location of the hook can be measured, for example, with laser sensors measuring the location of the bridge and rotary encoders, which measure how many rotations the wheels of the trolley and hoist motor have rotated.

In the second case, communication should be as efficient as possible, meaning the bandwidth usage, as well as the energy consumption of the sensor node, needs to be as low as possible. If the energy consumption is low enough, sensor nodes can be powered by batteries making them truly wireless. Because the computational power of sensor nodes is limited, the protocols should be lightweight in both use cases. In addition, easy implementation and availability of support are important factors. In this case, the stress is measured with a strain gauge, which is possible if the material properties are well known. The strain is measured once in a second and saved as an integer (4 bytes). Therefore, the data produced is 240 bytes per minute and 345.6 kB per day. The measurement data is sent to the data storage once in a minute. The requirements for both use cases for communication are summarized in Table 3.

Table 3. Requirements for use cases.

	Low latency	Low computational power	Low bandwidth usage	Low energy consumption	Security	Reliability	Easy implementation
Case 1	x	x			x	x	x
Case 2		x	x	x	x		x

This section presented the use cases, which are used in the assessment of the application layer protocols and communication technologies. Before moving to the assessment, the

layered architecture of the Internet is quickly presented in the following section helping the reader to perceive the overall picture of the communication.

3.3 The layered architecture of the Internet

The Internet protocol stack consists of five layers shown in Figure 12a. Each of Internet protocols belongs to one of these layers and provide services to the layer above and utilize the services offered by the layer below. The layered architecture provides the structure to the Internet and allows modular architecture. (Kurose & Ross, 2013, pp. 75–76) RFC 3439 (Bush & Meyer, 2002) discusses in more detail the benefits of layered architecture such as increased reliability and possibility to divide data into smaller packets. However, a more detailed description of the working principle of the Internet is out of the scope of this thesis.

The OSI model shown in Figure 12b is also a widely used model to describe the layered architecture of the Internet. In comparison to the five-layer internet protocol stack, it has two additional layers: presentation layer and session layer. The presentation layer is responsible for interpreting the data to the application layer including data compression and encryption (Kurose & Ross, 2013, p. 79) and the session layer provides connection and data exchange between presentation entities (ISO/IEC 7498-1, 1994, p. 35). In the five-layer Internet architecture, the functionalities of the two additional layers are implemented in the application layer (Kurose & Ross, 2013, p. 79). In this thesis, the focus is on the application layer protocols and communication technologies, which are located at the link and physical layer of the Internet protocol stack.

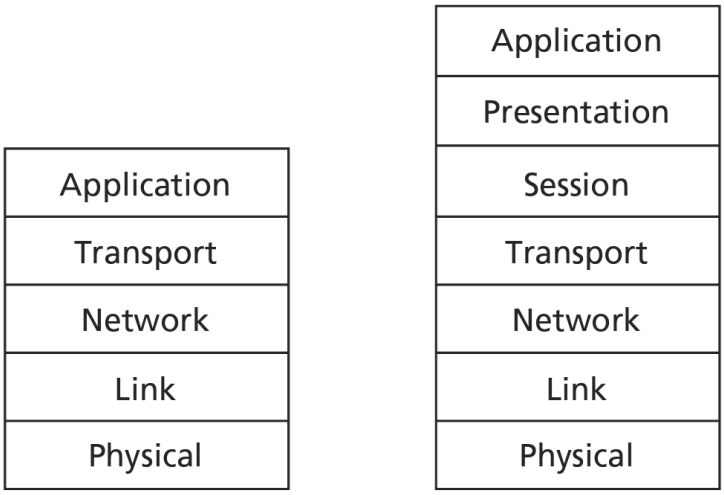


Figure 12. Five-layer Internet protocol stack (a) and Seven-layer ISO OSI reference model (Kurose & Ross, 2013, p. 76).

Sensor nodes that are able to use the Internet protocol stack presented above, are called IP-compatible. However, some sensor nodes are not capable of sending data directly over the Internet to the data server. In this case, they send data into a gateway (Figure 13), which collects data from multiple sensor nodes, translates the data into Internet protocol stack compatible and forwards it to the server or broker. (Kayal & Perros, 2017, p. 331) The IP-compatibility of a sensor node is determined by the communication technologies it supports. For example, short-range networks such as Bluetooth and ZigBee usually require a gateway whereas cellular networks such as 4G do not.

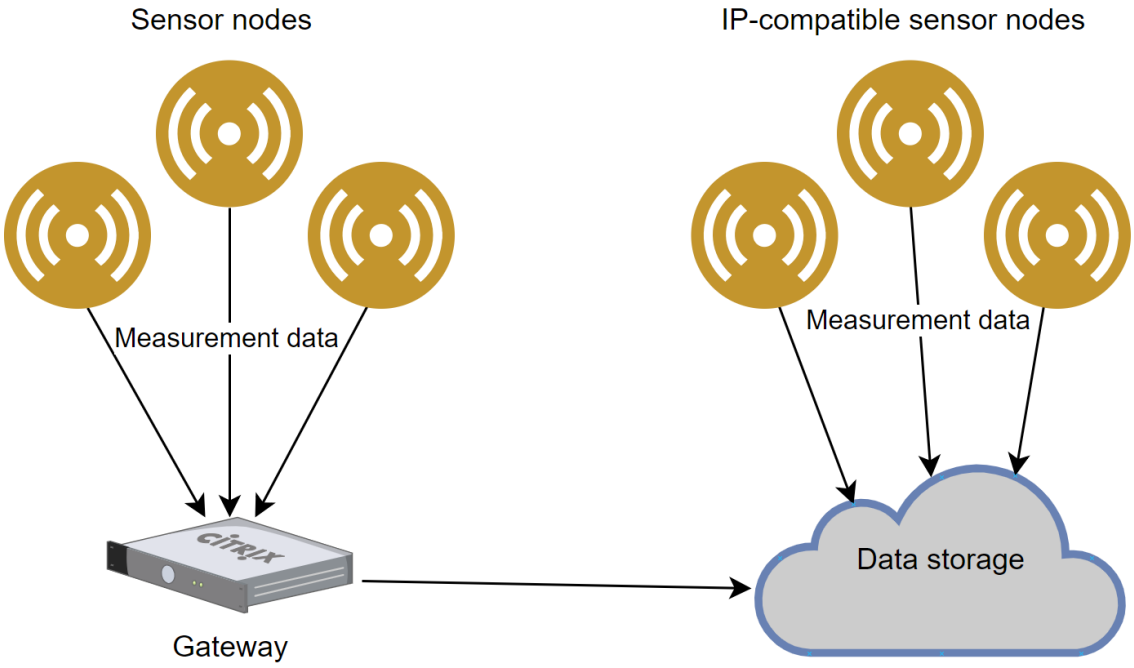


Figure 13. Some sensor nodes are capable of sending data directly over the Internet, whereas others require a gateway, which forwards data to the server.

3.4 Application layer protocols

The application layer is responsible for message exchange between the application's processes. Application layer protocols define the format and types of messages sent and how to respond to certain types of messages. Application protocols include for example HTTP (Web documents), SMTP (transfer of emails) and FTP (file transfer). (Kurose & Ross, 2013, pp. 77, 122–123) This thesis focuses on data transmission from sensor nodes to the data server. In this context, the most relevant properties for application layer protocols are latency, energy consumption, and suitability for constrained devices. For each protocol, the background, an overview of the architecture, message structure, and advantages/disadvantages are presented. The properties of examined protocols are summarized in Table 8 (p. 46), and, finally, their suitability for the use cases presented in the section 3.2 is assessed.

To enable the assessment of application layer protocols, the differences between underlying transport layer protocols, namely UDP (User Datagram Protocol) and TCP (Transmission Control Protocol), are discussed. UDP, defined in RFC 768 (Postel, 1980), is an unreliable and connectionless protocol and therefore the delivery of packet is not guaranteed (Kurose & Ross, 2013, pp. 216, 224–225). TCP, which core functionalities are defined in RFC 793, RFC 1122, RFC 2460, RFC, 2873, RFC 5681, RFC 6093, RFC 6298, and RFC 6991 (Duke et al., 2015), is connection-oriented, reliable protocol and, as can be seen from the number of RFCs, more complex than UDP (Kurose & Ross, 2013, pp. 216, 256).

TCP has congestion control and it resends packages until an acknowledgment is received. Therefore, an application developer can't control when an individual message is sent. The control is especially important with real-time applications, which work poorly with TCP's congestion control mechanism. With UDP, data is passed immediately to the network layer making it more suitable for real-time applications. (Kurose & Ross, 2013, pp. 225–226) TCP allows sequencing to arrange data segments, if they do not arrive in the same order as they were sent (Alani, 2014, p. 28).

As TCP is connection-oriented, the connection is needed to be established before sending data with a three-way handshake (Kurose & Ross, 2013, pp. 257–258). Therefore, the delay with TCP is higher than with UDP, which can send data immediately. UDP allows the server to handle more connections than TCP because, with TCP, connection state information is needed to be maintained for reliable data transfer and congestion control. Finally, UDP has smaller packet header overhead, 8 bytes, compared to TCP, which has 20 bytes overhead. (Kurose & Ross, 2013, pp. 225–226) The small overhead size is important in wireless networks with limited bandwidth and constrained devices.

In addition to TCP/UDP, TLS (Transport Layer security) should also be quickly addressed as it is used to secure communications, for example, with HTTP(S) (Rescorla, 2000) and AMQP (Al-Fuqaha et al., 2015, p. 2361). TLS, whose version 1.2 is specified in RFC 5246 (Dierks & Rescorla, 2008), has evolved from SLL version 3 and has a similar structure (Oppliger, 2009, p. 133; Kurose & Ross, 2013, p. 737). It works on top of reliable transport layer protocol such as TCP. The usage of TLS slows down the connection establishment, as additional handshaking is needed. The extra hand-shaking is used, for example, to select cryptographic algorithms and exchange of certificates. (Dierks & Rescorla, 2008, pp. 33–34)

In addition to the underlying transport layer protocol, the communication model is the major distinguishing factor between application layer protocols. The two most used communication models are request/response and publish/subscribe. In the request-response model, the client sends a request to a server, which then sends the response containing the requested resource. In the publish-subscribe model, there are publishers producing data, subscribers receiving data and, a broker distributing the data from publishers to subscribers (Liu et al., 2009, p. 7581).

Request-response protocols such as HTTP or MQTT often support RESTful interactions. REST is an architectural style for software first presented by Fielding (2000) in his doctoral thesis, which allows communication between systems. In practice, the resources identified by URL are at the core of the RESTful architecture. These resources can then be accessed, modified, added and removed using, for example, HTTP requests. These operations are called CRUD (Create, Read, Update and Delete) operations. HTTP is the de facto standard in RESTful communications, and it has a distinct request method for each of the operations to resources, namely GET, PUT, POST and DELETE. REST architectural style is often used with APIs (Application Programing Interfaces).

REST architectural style is designed for “distributed hypermedia systems” and it aims for enabling scalability, general interfaces, and security (Fielding, 2000, p. 105). Fielding describes the main principles of REST architecture as follows:

- Null Style, meaning system needs are examined as a whole
- Client-Server, in which a server offers services, which are requested by a client. The server then responds to these requests with a response.
- Stateless, meaning server does not store any session information about the client. Therefore, each request has to include all the information necessary for its execution.
- Cache. A response needs to be cacheable or non-cacheable. The response, if cacheable, is then stored and can be reused, which improves network efficiency.
- Uniform interface. A general interface between components with a standardized form of information is used.

- Layered system. Layered architecture allows scalability and use of legacy services. In the layered architecture, a component at one layer sees only the components they are directly interacting with.
- Code-On-Demand, which allows downloading of executable code. This is an optional feature.

3.4.1 HTTP

HTTP (Hypertext Transfer Protocol) is a widely used application layer protocol and a basic building block of the World Wide Web. It is a response-request protocol, meaning that the client sends a request to which server then responses. Requests have multiple methods such as GET, POST, PUT and DELETE each with its own use. For example, GET is used to retrieve data from server whereas POST is for sending data to the server. Response messages have also a type, which is indicated by status codes. For example, status 200 OK means successful request and the resource or information is in the payload of the response. (Kurose & Ross, 2013, pp. 124–125, 129–133; Alani, 2014, pp. 35–37) HTTP supports RESTful interactions and it is the most commonly used protocol with REST APIs. HTTP version 1.1 specification is defined in RFCs 7230-7235 (Fielding & Reschke, 2014, p. 4) and version 2 in RFC 7540 (Belshe, Peon & Thomson, 2015). There is also a secure version of HTTP, defined in RFC 2818, that runs over TLS (Rescorla, 2000).

HTTP uses TCP as an underlying transport layer protocol. Thus, a three-way handshake is needed to establish a connection, which means getting a response to a request takes at least two round-trip times. TCP offers reliable data transfer, so data sent over HTTP will eventually reach its destination. HTTP supports both persistent and non-persistent connections. Persistent connections are used as a default and they allow sending subsequent requests using the same connection. With persistent connections pipelining is also supported. With pipelining multiple requests can be sent in succession without getting a response after each request. (Kurose & Ross, 2013, pp. 125–129) However, HTTP/2 supports multiplexing, which is superior to pipelining (De Saxce, Oprescu & Chen, 2015). With non-persistent connections, the connection is closed after getting a response to the request. However, there can be multiple parallel connections, which quickens the process of getting multiple objects. (Kurose & Ross, 2013, pp. 126–128)

HTTP is a stateless protocol as the server doesn't store any information of clients (Kurose & Ross, 2013, p. 126). However, the server can set a cookie to a user-agent, which then sends the cookie header with subsequent requests (Barth, 2011). Cookies are sent with response messages and can be used to identify the user (Kurose & Ross, 2013, pp. 134–136).

Headers in both requests and responses are in ASCII text format, which makes them human-readable. However, data can be at any format specified by the *Content-Type* header. HTTP/2 offers a possibility to compress header data with HPACK algorithm, which is beneficial as headers usually contain overlapping information (De Saxce et al., 2015, p. 294).

The HTTP request consists of a request line, which is always the first line of the message, followed by header lines and finally an entity body in which the actual data is stored. Request line includes the method, URL of the server and protocol version. There might be multiple header lines, which are name-value pairs. The request line is separated from header lines and header lines are separated from each other by a carriage return and line

feed. After header lines is an extra carriage return and line feed followed by the possible data (for example with GET request, the data is not sent in the entity body). An example of an HTTP request is shown below (Figure 14) and a general format of an HTTP request is shown in Figure 16.

```
1  POST /path HTTP/1.1
2  Host: www.somewebsite.com
3  Connection: Keep-Alive
4  User-agent: Mozilla/5.0
5  Content-Type: application/x-www-form-urlencoded
6  Content-Length: 234
7
8  [data]
```

Figure 14. An example of HTTP request.

An HTTP response follows the same format as a request, but the request line is replaced with the response line, which consists of version, status code, and explanation of the status code. An example of a response is shown below (Figure 15) and the general format of a response message is shown in Figure 17.

```
1  HTTP/1.1 200 OK
2  Connection: Keep-Alive
3  Date: Wed, 24 Oct 2018 07:00:12 GMT
4  Server: Apache/2.4.6
5  Content-Length: 1234
6  Content-Type: application/json
7
8  [data]
```

Figure 15. An example of HTTP response.

As HTTP is a text-based protocol, its overhead size is large compared to protocols with bit formatted header. In addition, HTTP has high energy consumption and latency, it requires more computational resources than other application layer protocols, and it is inefficient in terms of bandwidth usage (Naik, 2017). For these reasons, HTTP is not especially suitable for constrained sensor nodes.

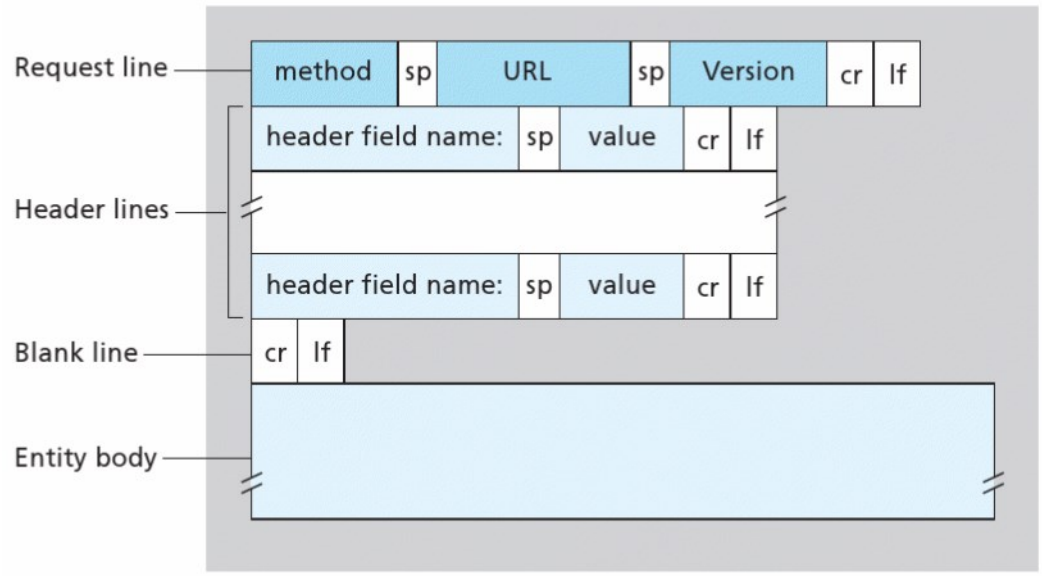


Figure 16. The general format of the HTTP request message (Kurose & Ross, 2013, p. 131).

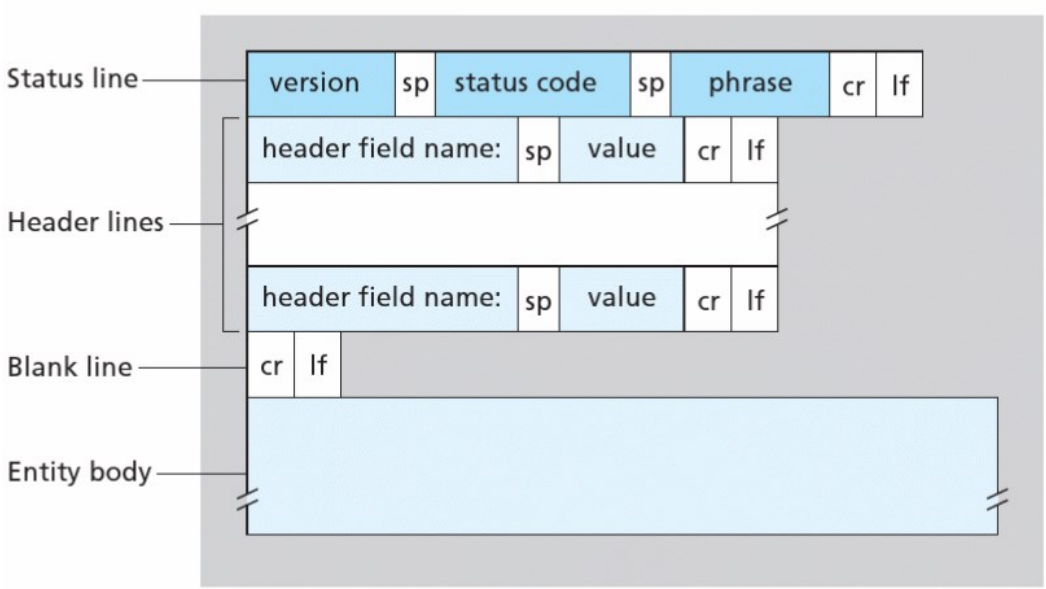


Figure 17. The general format of the HTTP response message (Kurose & Ross, 2013, p. 133).

3.4.2 MQTT

MQTT (Message Queuing Telemetry Transport) is a lightweight publisher/subscriber messaging protocol developed by IBM (OASIS Standard, 2014, p. 1; Chen & Kunz, 2016, p. 2). It is open-sourced, easy to implement and can be used with constrained devices (OASIS Standard, 2014, p. 1). MQTT is used by several applications in health care, monitoring, and energy metering as well as by Facebook messenger (MQTT.org, 2011; Al-Fuqaha et al., 2015, p. 2354).

Publisher/subscriber architecture uses less bandwidth and computational power than request/response protocols such as HTTP because clients do not need to ask updates. Therefore it is more suitable for IoT communication. (Karagiannis et al., 2015, p. 14) The MQTT's publisher/subscriber architecture (Figure 18) has three components: publisher, broker and subscriber (Al-Fuqaha et al., 2015, p. 2354). Publisher, which can be for example sensor node, publishes messages with specific topics and sends them to a broker. Subscriber (server) then subscribes these topics and, finally, the broker forwards messages from each topic to the subscriber of that specific topic. (Dürkop, Czybik & Jasperneite, 2015, p. 72)

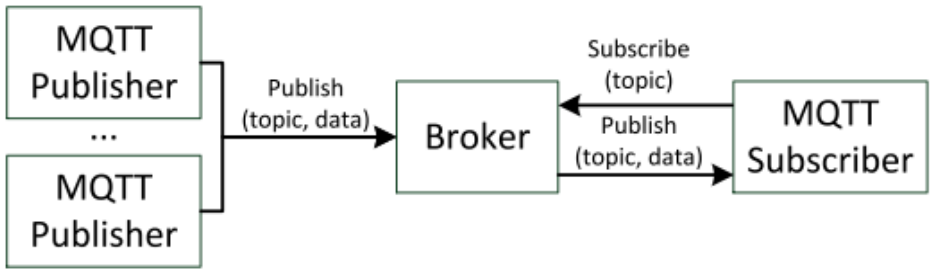


Figure 18. MQTT architecture (Dürkop et al., 2015, p. 72).

Kraijak & Tuwanut (2015, p. 30) emphasize that the broker is a key element in the system. If a centralized broker fails, the system fails (Hakiri et al., 2015, p. 51). There are multiple MQTT brokers in the market such as IBM Message Sight, HiveMQ, and open-source Eclipse Mosquitto, some of which offer commercial broker service and further features

on top of standard MQTT implementation (Kraijak & Tuwanut, 2015, p. 30; Eclipse Foundation, 2018).

MQTT runs over TCP, but it is able to use also other network protocols, which offer ordered, lossless and bidirectional connections (OASIS Standard, 2014, p. 1). However, Hakiri et al. (2015, p. 51) question the suitability of TCP for an environment in which packet loss is high and computational resources are limited. Because of TCP's poor error handling in the lossless network, three quality of service levels to message delivery (Dürkop et al., 2015, pp. 70–72) are implemented in MQTT (OASIS Standard, 2014, pp. 1–2, 52–55):

- QoS level 0, "At most once", indicates that message is delivered according to the best efforts, but the message loss might occur. Messages are not resent, and the receiver does not acknowledge messages. Therefore, the message arrives "at most once".
- QoS level 1, "At least once", in which message delivery is guaranteed, but duplicates might occur.
- QoS level 2, "Exactly once", meaning message delivery is guaranteed and no duplicates are sent.

There are no built-in security mechanisms in MQTT and the responsibility of implementing security lies with the application developer. TLS and AES/DES are commonly used mechanisms to achieve security. (OASIS Standard, 2014, pp. 60–61) In addition, Singh et al. (2015) present a secure version of MQTT protocol called SMQTT, which utilizes Key/Ciphertext Policy-Attribute Based Encryption (KP/CP-ABE) and Elliptic Curve Cryptography (ECC).

MQTT message consists of a fixed header, variable header, and payload shown in Table 4. The fixed header contains message type, several flags depending on message type and *Remaining length* field, whose size varies from one byte to four bytes. Therefore, the minimum size of the MQTT message is only two bytes. The variable header is present only with certain message types and contains specific information to that type of message. After the variable header is the payload of the message. (OASIS Standard, 2014, pp. 16–22)

Table 4. MQTT message structure (Singh et al., 2015, p. 747).

bit	7	6	5	4	3	2	1	0
byte 1	Message Type				DUP Flag	QoS Level		Ret
byte 2	Remaining length							
Variable Header								
Payload								

The benefits of MQTT include a bit formatted header with a minimum size of only two bytes. In addition, it has low CPU and memory usage as well as low latency in the low sampling rate. The support for constrained devices is excellent. (Talaminos-Barroso et al., 2016, p. 8). There is also a micropython library available for MQTT (GitHub, Inc., 2019b). The disadvantage of MQTT is that latency is high with high sampling rates (Talaminos-Barroso et al., 2016, p. 8).

MQTT-SN (MQTT for Sensor Networks) is a separate protocol from MQTT, which is designed for wireless networks with constrained devices. Therefore, even though MQTT-

SN follows the same design principles, there are multiple differences between the protocols. (Stanford-Clark & Truong, 2013, p. 4) Firstly, instead of TCP, it uses a UDP as an underlying protocol (Mun, Dinh & Kwon, 2016, p. 556), which is more suitable for constrained devices (Nguyen, Laurent & Oualha, 2015, p. 22). In addition, topic names are replaced in PUBLISH messages (Table 5) with topic ids, which length is only two bytes, to minimize the overhead, and there is a possibility to use predefined topics to start messaging without the need to first register the topic. There is also a discovery procedure to help the configuration of the devices. Finally, sleeping of devices is supported by buffering of the messages to reduce energy consumption. (Stanford-Clark & Truong, 2013, pp. 4–5)

Table 5. The structure of PUBLISH message in MQTT-SN protocol (Stanford-Clark & Truong, 2013, p. 13).

Length (octet 0)	MsgType (1)	Flags (2)	TopicId (3-4)	MsgId (5-6)	Data (7:n)

In MQTT-SN protocol, clients such as sensors are not directly communicating with MQTT broker. Instead, they are connected to a gateway, which converts MQTT-SN messages into MQTT messages and then sends them to the broker. The gateway can also be integrated to a broker as shown in Figure 19. If clients can't access gateway directly, an MQTT-SN forwarder can be used to transmit messages from clients to the gateway. (Stanford-Clark & Truong, 2013, p. 5)

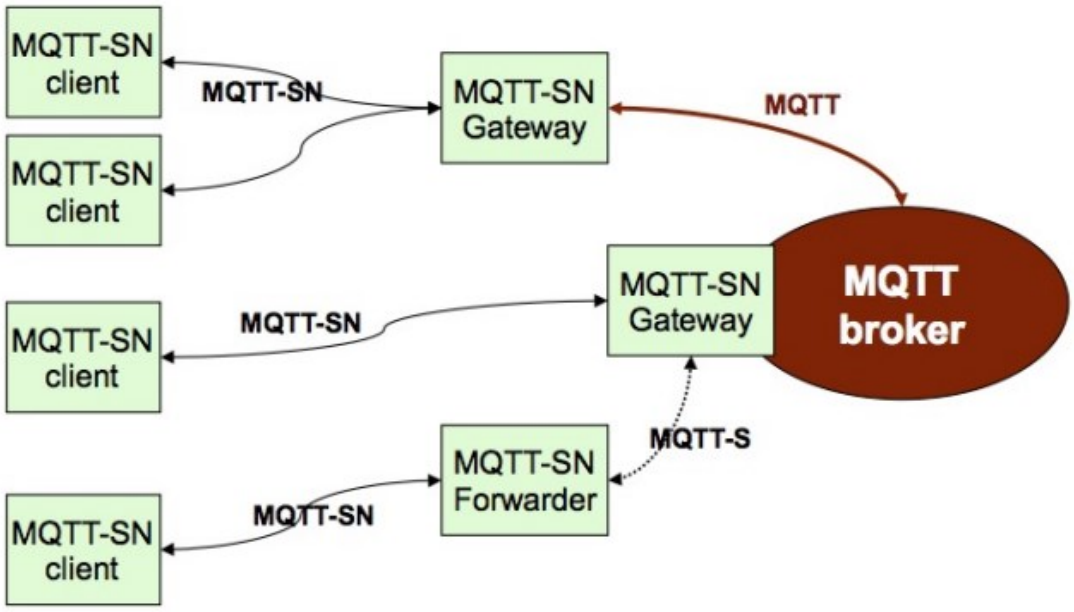


Figure 19. MQTT-SN architecture (Stanford-Clark & Truong, 2013, p. 5).

3.4.3 CoAP

CoAP (Constrained Application Protocol), defined in RFC 7252 (Shelby, Hartke & Bormann, 2014), is a request/response protocol for M2M communication and IoT developed by IETF (Internet Engineering Task Force) (Karagiannis et al., 2015, p. 4; Yassein, Shatnawi & Al-zoubi, 2016, p. 1). It is designed to provide RESTful interactions for constrained devices and networks. CoAP runs on top of UDP by default but can utilize also other transport methods such as SMS or TCP. (Shelby et al., 2014, pp. 5, 15) There are no built-in security mechanisms in CoAP, yet DTLS (Datagram Transport Layer Security) can be used on top of UDP to secure communication (Karagiannis et al., 2015, p. 4).

However, it adds overhead approximately 13 bytes per datagram (Shelby et al., 2014, p. 69).

CoAP supports CRUD (Create, Retrieve, Update and Delete) operations by using the same methods (GET, POST, PUT, DELETE) as HTTP enabling RESTful interaction (Al-Fuqaha et al., 2015, p. 2535). In addition, CoAP utilizes similar response codes as HTTP (Kovatsch, Lanter & Shelby, 2014, p. 1). Resources are identified and located by URIs (Shelby et al., 2014, p. 59) and an additional non-RESTful feature called resource observation can be used to update the state of the resources (Tanganelli, Vallati & Mingozzi, 2015, p. 2). Resource observing, defined in RFC 7641 (Hartke, 2015), utilizes publish/subscribe design in which client subscribes updates for a specific resource and is notified when the status of the resource changes. Another additional feature CoAP supports is a block-wise transfer, defined in RFC 7959 (Bormann & Shelby, 2016), which is used to prevent IP fragmentation. IP fragmentation occurs when a large amount of data is being sent and the data is divided into multiple messages at the Network layer, which lowers the efficiency of communication. The block-wise transfer prevents the IP fragmentation by splitting the payload into a chain of messages in the application layer instead of in the Network layer. (Tanganelli et al., 2015, p. 2)

CoAP architecture can be described as consisting of two layers: the messaging layer and the request/response layer. The messaging layer is responsible for communication over UDP and ensures the reliability of the communication. The request/response layer is responsible for implementing RESTful communications. (Al-Fuqaha et al., 2015, p. 2353)

CoAP header is in a binary form and its structure is shown in Table 6. It consists of a fixed part, which is four bytes and includes the version, message type such as confirmable or reset, token length, code such as *4.04 Not Found*, and message ID. The fixed part is followed by token, whose length varies from 0 to 8 bytes, options, which also vary in size, and finally payload. (Shelby et al., 2014, pp. 15–17) Compared to for example HTTP header, the header size is significantly smaller as the binary format is used.

Table 6. CoAP header structure (Shelby et al., 2014, p. 16).

0-1	2-3	4-7	8-15	16-31
Version	Type	Token length	Code	Message ID
Token (if any, length defined by Token length)				
Options (if any)				
1 1	1 1	1 1 1 1	Payload (if any)	

CoAP has low CPU, memory and bandwidth usage (Talaminos-Barroso et al., 2016, p. 8) making it suitable for constrained devices. In addition, the protocol is simple and supports resource discovery. However, it has high latency and it is not suitable for real-time communication. (Talaminos-Barroso et al., 2016, p. 8)

3.4.4 XMPP

XMPP (Extensible Messaging and Presence Protocol) is commonly used communication and messaging protocol in IoT (Yassein et al., 2016, p. 2) defined in RFC 6120 and 6121 (Saint-Andre, 2011a, 2011b). It was first introduced by the Jabber open-source community in 1999 and have been further developed and standardized by IETF (Kubler et al., 2014, p. 241). The protocol allows “near-real-time” communication (Saint-Andre, 2011a, p. 8) and is used for example multi-party chatting and video calls (Al-Fuqaha et al., 2015,

p. 2355). XMPP uses TCP as an underlying transport layer protocol and offers both publish/subscribe and request/response models for communication. There is also built-in security in the protocol, which utilizes SSL/TLS. (Karagiannis et al., 2015, p. 5)

XMPP typically uses a decentralized architecture (Saint-Andre, 2011a, p. 148) in which streams consisting of XML stanzas are used for communication (Kubler et al., 2014, p. 241). XML stanzas are the basic units of communication in XMPP (Saint-Andre, 2011a, pp. 20–21). As the stanzas are text-based (Al-Fuqaha et al., 2015, p. 2355) and contain unnecessary tags, the overhead size is large (Karagiannis et al., 2015, p. 5). However, EXI (Efficient XML Interchange) (The World Wide Web Consortium, 2014) can be used to compress stanzas (Al-Fuqaha et al., 2015, p. 2355). The use of XML also requires additional computational power as it is necessary to parse the messages (Karagiannis et al., 2015, p. 5).

There are three types of stanzas: 1) message, which is used for sending data from one entity to another 2) presence, which follows publish/subscribe pattern and is used for "broadcasting information about network availability" to multiple entities 3) IQ (info/query), which follows request/response pattern. (Saint-Andre, 2011a, pp. 21, 104) An example of a structure of a message stanza from a client to a server is presented in Figure 20.

```
<message from='juliet@im.example.com/balcony'
         to='romeo@example.net'
         xml:lang='en'>
  <body>Art thou not Romeo, and a Montague?</body>
</message>
```

Figure 20. An example of XML stanza in XMPP (Saint-Andre, 2011a, p. 68).

XMPP is an established and standardized protocol, and there is a large amount of open-source software available (Kirsche & Klauck, 2012, p. 456). It is suitable in IoT communication as it offers low latency, supports small messages (Yassein et al., 2016, p. 2), and can be used without middleware or protocol gateways (Kirsche & Klauck, 2012, p. 456). However, XMPP has also some disadvantages such as high CPU and bandwidth usage, no support for QoS options and insufficiency for real-time applications (Talaminos-Barroso et al., 2016, p. 8). Chen & Kunz (2016, p. 1) even left it out from their article as the implementations of XMPP were only for chatting/messaging applications instead of an IoT and the development of the protocol has been stopped. However, the development of the protocol seems to have continued as extensions to XMPP are currently developed by the XSF (XMPP Standards Foundation) (xmpp.org, 2019).

3.4.5 AMQP

AMQP (Advanced Message Queuing Protocol) was introduced in 2003 by John O'Hara at JPMorgan Chase (Luzuriaga et al., 2015, p. 931), and was later standardized by OASIS (Yassein et al., 2016, p. 3). In 2014, it was accepted as an ISO/IEC standard (ISO/IEC 19464:2014, 2014). AMQP is designed for business messaging (AMQP v1.0, 2011, p. 6) and is commonly used in commercial platforms (Yassein et al., 2016, p. 3). AMQP uses a reliable transport layer protocol such as TCP and ensures security by using TLS and SASL negotiation. The protocol follows a publish/subscribe model but, in addition, point-to-point communication is supported. (Al-Fuqaha et al., 2015, pp. 2355, 2361)

AMQP consists of two layers: a binary protocol for transport of messages and messaging layer, which defines the message format (AMQP v1.0, 2011, p. 6). The transport layer

has three main actors: Publisher, Subscriber/Consumer and Broker/Server shown in Figure 21. A publisher sends messages to exchange, which then determines to which queue messages are forwarded. Every queue is created and used by one specific subscriber, and messages are stored to the queue. (Subramoni et al., 2008, p. 2) Finally, the message is sent from the queue to the receiver (Al-Fuqaha et al., 2015, p. 2355). This architecture makes the system reliable even if there are interruptions in the network (Johnsen et al., 2013, p. 3).

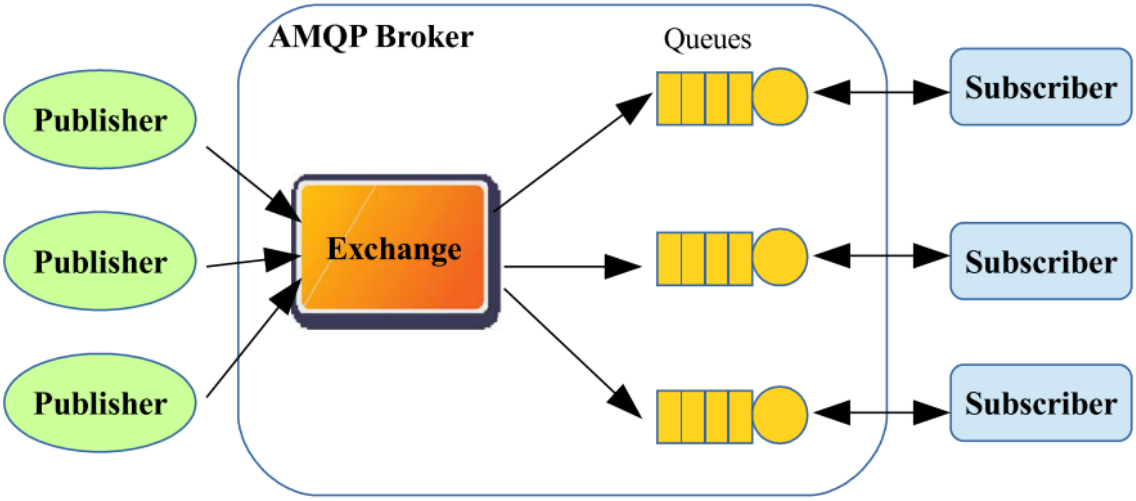


Figure 21. The architecture of AMQP's publish/subscribe mechanism (Al-Fuqaha et al., 2015, p. 2355).

The messaging layer works on top of the transport layer and ensures interoperability. It defines the message format, states of the messages, distribution nodes, and sources and targets. (AMQP v1.0, 2011, p. 73) An AMQP message, whose structure is shown in Table 7, is self-contained and has no limit for the message size (Luzuriaga et al., 2015, p. 1). AMQP supports the following guarantees for the message delivery (AMQP v1.0, 2011, pp. 51–52), which are similar to MQTT:

1) At-most-once
2) At-least-one
3) Exactly-once.

Table 7. The structure of an AMQP message (AMQP v1.0, 2011, p. 74).

			Bare message			
Header	Delivery-annotations	Message-annotations	Properties	Application-properties	Application-data	Footer
Annotated message						

AMQP offers high interoperability between different vendors and extendibility (Talaminos-Barroso et al., 2016, p. 8). In an IoT environment, it is used for message exchange and communication focused applications (Yassein et al., 2016, p. 3). AMQP has low memory consumption making it suitable for constrained devices. However, the availability of open-source software for constrained devices is poor, and automatic discovery of devices is not supported. In addition, the protocol is not suitable for real-time applications. (Talaminos-Barroso et al., 2016, p. 8)

3.4.6 DDS

DDS (Data Distribution Service) is standardized by Object Management Group (2015a) and provides reliable real-time communication for IoT applications and M2M communication (Al-Fuqaha et al., 2015, p. 2356). For predictable behavior (Talaminos-Barroso et al., 2016, p. 6), 23 QoS policies are defined, which allows controlling of, for example, security, priority, and reliability. DDS follows a publish-subscribe model and uses brokerless architecture. (Al-Fuqaha et al., 2015, p. 2356) The protocol does not specify a transport layer protocol, hence both TCP and UDP are supported. Therefore, different implementations are not able to interoperate with each other. (Object Management Group, 2013, p. 5). The security model and Service Plugin Interface (SPI) architecture, which allows "out-of-box security and interoperability between compliant DDS applications", are standardized in (Object Management Group, 2018).

The architecture of DDS, shown in Figure 22, consists of two layers: Data-Centric Publish-Subscribe (DCPS) and an optional Data-Local Reconstruction Layer (DLRL) (Al-Fuqaha et al., 2015, p. 2356), which works on top of DDS and integrates DDS into application layer by offering interface to access data (Object Management Group, 2015b, pp. 1–3). The DCPS layer consist of the following entities (Al-Fuqaha et al., 2015, p. 2356; Object Management Group, 2015a, pp. 6–7):

1) Publisher, which distributes the data
2) DataWriter, which passes the data from application to the publisher
3) Subscriber, which receives the published data and makes it available to the application
4) DataReader, which application uses to access the data
5) Topic, identified by a name unique in the domain, which acts as a link between DataReader and DataWriter.

DDS supports automatic discovery of information and has high scalability. In addition, latency and jitter are low, which along with high predictability allows the use of the protocol in real-time applications. However, due to the automatic discovery, memory consumption and the use of computational resources are high, and because of decentralized architecture, the CPU usage grows exponentially, when publishing rate increases. The development and configuration are also rather complex compared to other protocols and the availability of open-source libraries for constrained is inadequate. (Talaminos-Barroso et al., 2016)

3.4.7 OPC UA

OPC UA (Open Platform Communications Unified Architecture) is a protocol designed for industrial use suitable for IIoT and M2M communications (OPC Foundation, 2017, p. 8). It is standardized in IEC 62541 parts 1-11, 13 and 100 (IEC TR 62541-1:2016, 2018), and continuously developed by OPC foundation (Gruner, Pfrommer & Palm, 2016, p. 1833). OPC UA provides secure communication, robustness, and a mechanism for quick recovery of communication failure. The protocol is platform-independent and supports multiple types of servers from PLC to enterprise servers. As some servers are resource constrained, they are allowed to provide only a subset of the broad range of capabilities OPC UA servers may implement. These subsets of capabilities are called profiles, and clients can utilize them in communication with server. (Sauter & Lobashov, 2011, p. 707; OPC Foundation, 2017, pp. 9–10)

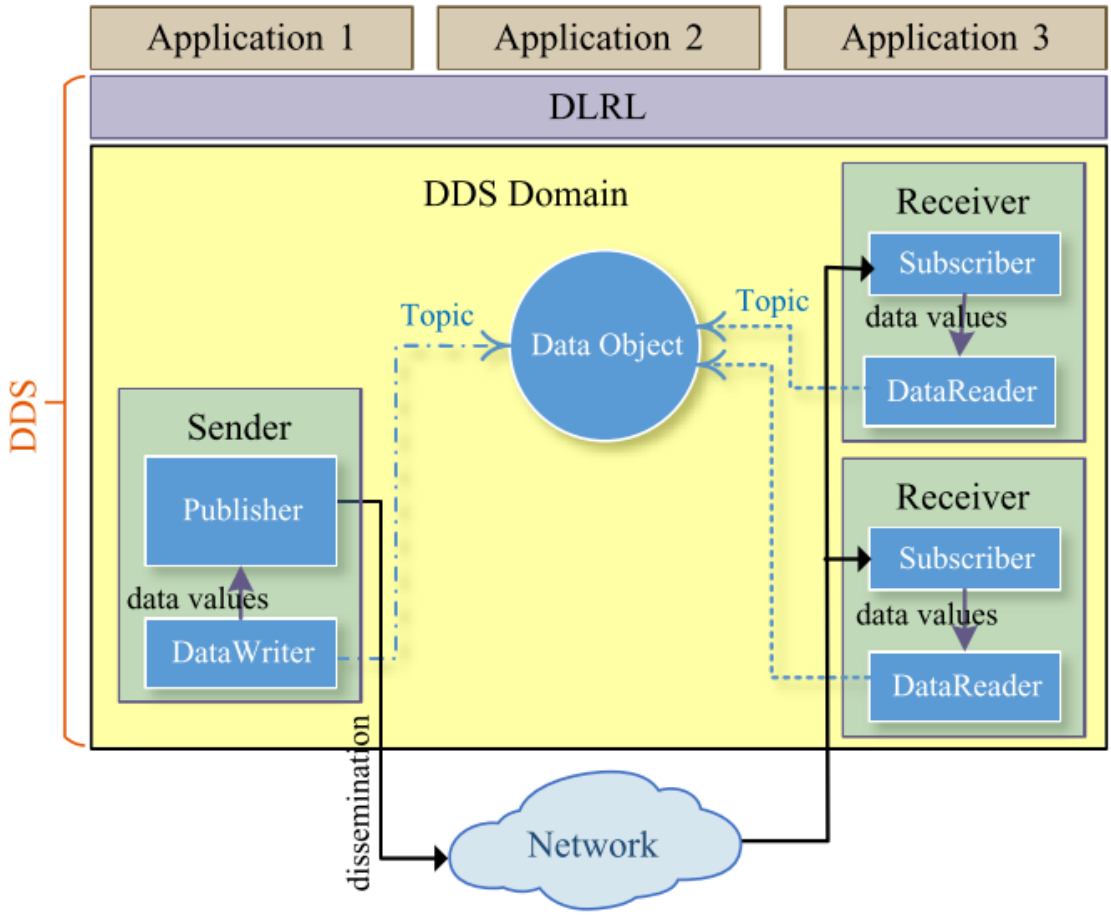


Figure 22. The architecture of DDS (Data Distribution Service) (Al-Fuqaha et al., 2015, p. 2356).

OPC UA supports both Client/Server and Publish/Subscribe models. In the client/server model, servers offer services, which are grouped into Service Sets such as SecureChannel Service Set and Session Service Set. Each server specifies to clients, which of these service sets they offer. (OPC Foundation, 2017, pp. 9, 19) In addition, servers offer Alarms and Conditions, which are asynchronous notifications, and Historical Access (access to historical data) (Sauter & Lobashov, 2011, p. 707).

In the PubSub architecture, two types of Message Oriented Middleware (MOM) are used to distribute messages between publishers and subscribers (OPC Foundation, 2017, p. 18):

1) A broker-less, in which MOM offers network infrastructure, which routes messages between publishers and subscribers, who use, for example, UDP multicast as a transport protocol.
2) A broker-based, in which MOM is a broker, and "publishers and subscribers use standard messaging protocols like AMQP or MQTT to communicate with broker." Published messages are distributed into queues, which subscriber can listen.

The architecture of the OPC UA server is shown in Figure 23.

OPC UA is able to use TCP, WebSockets or HTTPS for transportation and supports three encodings, namely XML/text, UA Binary, and JSON (OPC Foundation, 2017, p. 10). XML has low efficiency in terms of bandwidth usage and it needs to be parsed, which restricts its suitability for constrained devices (Sauter & Lobashov, 2011, p. 707). The information model of OPC UA is object-oriented (Gruner et al., 2016, p. 1834). The objects are organized as nodes in a graph (Sauter & Lobashov, 2011, p. 707), which is called

AddressSpace (OPC Foundation, 2017, p. 12). The benefits of OPC UA include the robustness as it is designed for industrial use. In addition, it supports both client/server and publish/subscribe models making it flexible and suitable for various applications.

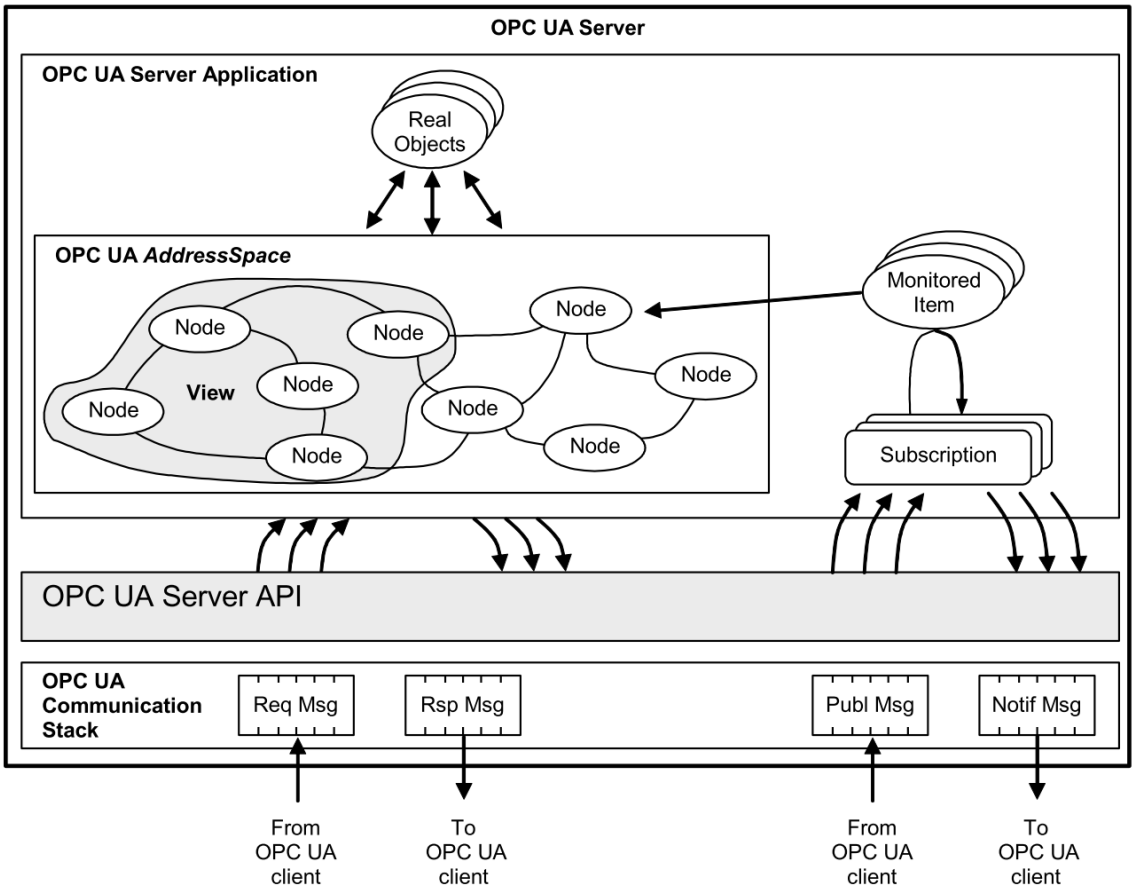


Figure 23. OPC UA Server architecture (OPC Foundation, 2017, p. 15).

3.4.8 Comparison

Several papers comparing application layer protocols in the context of IoT and M2M communications have been published: 1) Dürkop et al. (2015) assess the performance of M2M protocols over cellular networks in a lab environment, 2) Talaminos-Barroso et al. (2016) evaluates performance of M2M protocols in context of eHealth applications, 3) Mun et al. (2016) examines protocols suitable for resource-constrained applications, 4) Chen & Kunz (2016) investigate the performance of M2M protocols in lossy and low-bandwidth wireless network from the patient health monitoring system view, 5) Naik (2017) focuses on messaging protocols for IoT, and 6) Kayal & Perros (2017) compare the suitability of IoT application layer protocols for a smart parking system. Table 8 summarizes the properties of application layer protocols and their relative performance based on the above-mentioned studies and literature review on pp. 32–44 The relative performance is estimated in a scale of low-medium-high as the actual performance of the protocol is case sensitive and the depends on for example dynamic network conditions (Naik, 2017, p. 3). If there were conflicting results, results from (Talaminos-Barroso et al., 2016) were used because the study contains most of the protocols of interest. There is a lack of research papers containing performance comparison of OPC UA to other protocols. Therefore, OPC UA is missing some information.

The suitability of protocols for use cases presented in section 3.2 (pp. 30–32) is evaluated based on the literature review. At this point, it should be noted that TCP, whose retransmission mechanism is not working properly with lossy networks, is not especially suitable for wireless networks (Dürkop et al., 2015, p. 71). Therefore, when choosing an application layer protocol, the network type used should be considered. In this comparison, it is supposed that the network is wireless, but the packet loss rate is rather small. Therefore, UDP is not preferred over TCP.

Table 8. Comparison of application layer protocols based on the literature review.

	HTTP	MQTT	CoAP	XMPP	AMQP	DDS	OPC UA
Comm. model	Request/ response	Publish/ subscribe	Request/ response	Request/ response & publish/ subscribe	Publish/ subscribe & request/ response	Publish/ subscribe	Publish/ subscribe & client/server (services)
Architecture	Client/ server	Client/ Broker	Client/ server	Client/ server	Client/ broker	Client/ server	Client/ server and Client/broker
Transport	TCP	TCP or UDP (MQTT-SN)	UDP	TCP	TCP	TCP & UDP	TCP/WS/HTTPS[1] & UDP/AMQP/ MQTT[2]
QoS	Not supported	3 levels	Confirmable/ Non-confirmable	Not supported	3 levels	23 policies	Not supported
Real-time	Not supported	Not supported	Not supported	"near-real-time"	Not supported	Supported	Not supported
Security	SSL/TLS	SSL/TLS	DTLS	SSL/TLS	SASL, SSL/TLS	Built-in	Built-in
Encoding	Text	Binary	Binary	XML/text/ EXI	Binary	Not applicable	XML/text/ JSON/UA Binary
Overhead*	High	Low	Low	Medium	Low	Low	Medium
Jitter*	-	Low	High	Medium	High	Low	-
Latency*	High	Medium	High	High	Medium	Low	Low[3]
Energy consumption*	High	Medium	Low	-	-	-	-
Bandwidth usage*	High	Low to medium	Low	Medium to high	Low	High	-
CPU usage*	High	Low	Low	High	Low	Medium	-
Memory consumption*	High	Medium	Medium	Low	Low	High	-

*Relative, [1](client/server), [2](publish/subscribe), [3]Transmission time (Dürkop et al., 2015).

In the first use case, sensor data is used to control the physical twin in real-time. Thus, secure, robust and low-latency connection is required. The only protocol of those examined, which is capable of real-time communication is DDS. In addition, it offers built-in security, robustness, low-latency and high predictability. Therefore, it is an obvious choice for the first use case. The drawbacks of DDS include high bandwidth usage and

memory consumption as well as medium CPU usage, which restricts its use with very constrained environments.

The second use case, in which the strain of the bridge is measured periodically, has not strict requirements for the communication in terms of latency, data rate or robustness. Therefore, all protocols are suitable for that use case to some extent. However, low energy consumption, suitability for constrained devices and overall efficiency are desirable properties to make sensor nodes battery-operated and, thus, truly wireless. The most emphasis in this comparison is given to the suitability for constrained devices, which includes low energy consumption and bandwidth usage. The most suitable protocols are therefore CoAP, MQTT and AMQP.

MQTT is a publish/subscribe protocol, CoAP is a request/response protocol, and AMQP supports, in addition to the publish/subscribe model, point-to-point communication. In the second use case, the data is sent to a single entity: the data storage of a digital twin. Therefore, publish-subscribe is not advantageous over the request/response pattern. Both MQTT and AMQP use TCP as an underlying transport layer protocol, while CoAP uses UDP. Thus, CoAP should perform better in lossy networks because TCP's congestion control is not suitable for those types of networks.

The bandwidth usage is quite similar for each of these protocols as well as the CPU usage, but AMQP uses slightly less memory (Talaminos-Barroso et al., 2016, pp. 5–6). CoAP has lower energy consumption than MQTT with package size less than 1024 bytes. With larger package sizes, the energy consumption of CoAP increases due to packet fragmentation and, thus, MQTT has lower energy consumption with large packet sizes. (Mun et al., 2016, p. 558) Chen & Kunz (2016, pp. 4–5) note that with low packet loss rate and latency, MQTT consumes more bandwidth than CoAP, but increasing both reduces the bandwidth consumption, while CoAP has steady bandwidth consumption. Therefore, with high packet loss and latency, MQTT performs better than CoAP in terms of bandwidth usage.

Talaminos-Barroso et al. (2016, p. 8) claim that AMQP lacks open-source libraries for constrained devices and CoAP is missing support for tools and libraries. The availability of libraries makes the implementation of MQTT easier than CoAP and AMQP. Because the properties of the protocols are otherwise quite similar, this makes MQTT the recommended choice for the second use case. It is also implemented on the developed sensor configurator platform. However, in lossy networks CoAP is preferred choice, because it uses UDP instead of TCP as an underlying transport layer protocol. In general, the easiness of the implementation and integration to existing systems as well as the availability of support are important factors, when choosing application layer protocol. In addition, the used communication technology should be considered when choosing an application layer protocol and vice versa because, for example, the high packet loss in a network have different effects on different application layer protocols.

3.5 Communication technologies

This section presents a short review of wireless communication technologies used for M2M, IoT, and IIoT. Communication technologies can be divided into two categories: Low Power Wide Area Networks (LPWAN) and short-range networks (Al-Sarawi et al., 2017, p. 685). With short-range networks, a gateway is needed for wide area connectivity (Aijaz & Aghvami, 2015, p. 103). This literature review examines both types of communication technologies.

3.5.1 Low power wide area networks (LPWANs)

LPWANs have a long range up to a few tens of kilometers depending on the environment (Petäjäjärvi et al., 2015), operate usually at unlicensed ISM (Industrial, Scientific and Medical) bands at 169, 433, 868/915 MHz, and 2.4 GHz (Georgiou & Raza, 2017, p. 162), and have a low bitrate and energy consumption (S. Raza et al., 2017, p. 855). In this review, also cellular networks are included to LPWAN as also Al-Sarawi et al. (2017) have done in their review.

Cellular networks include 2G/3G/LTE and 5G technologies (Karagiannis et al., 2015, p. 1). 4G also known as LTE-A (Long Term Evolution Advanced) is commonly used with cell phones, offers high data rate up to 3 Gbps uplink and 1.5 Gbps downlink (Gupta & Jha, 2015, p. 1211), and low latency up to below 5 ms (Gandotra, Kumar Jha & Jain, 2017, p. 11). To serve the needs of M2M and IoT communication such as low energy consumption, 3GPP (3rd Generation Partnership Project) is developing new standards based on the existing ones. These new standards try to utilize the existing cellular network infrastructure. As a result, for example, LTE eMTC (Long Tem Evolution enhancements for Machine Type Communications and NB-IoT (Narrow Band IoT) have been released. (U. Raza, Kulkarni & Sooriyabandara, 2017, p. 864)

NB-IoT specifications were released in 2016 by 3GPP (Mekki et al., 2018, p. 3). NB-IoT is able to utilize GSM (Global System for Mobile Communications), GPRS (General Packet Radio Service), and LTE networks. The existing LTE infrastructure needs only a software update to be compatible with NB-IoT. The data rate is low, up to 250 kbps for multi-tone downlink and 20 kbps for the uplink. (U. Raza et al., 2017, p. 865) NB-IoT implements only a limited set of features of LTE and is optimized for low-power IoT devices. It allows connection of 100 000 devices to each cell. (Mekki et al., 2018, pp. 3–4)

5G increases the data rates up to 10 Gbps (Li et al., 2017, p. 1510) and lowers the latency to under 1 ms (Gandotra et al., 2017, p. 11). The 5G is expected to offer a massive number of connections, high data rate, security, and reliability as well as low latency and energy consumption. 5G has multiple technologies making it suitable for IoT use such as wireless network function virtualization (WNFV), which allows dividing network into multiple virtual networks providing processing capability, and Direct Device to Device (D2D), which allows communication between devices without base station (Li, Xu & Zhao, 2018, pp. 4–6).

LoRaWAN (Long Range Wide Area Network) operates at unlicensed sub-GHz ISM bands and offers data rate from 300 bps to 50 kbps. The chirp spread spectrum (CSS) modulation used allows spreading of the signal over a wider bandwidth. By varying the spreading factor, the trade-off between high data rate and high range can be selected. (Mekki et al., 2018, pp. 2–3) LoRaWAN divides end-devices to three classes (U. Raza et al., 2017, p. 866):

- Class A, in which a device listens to downlink communication only a short time after it has sent data.
- Class B, in which the downlink is listened only at certain times.
- Class C, in which the downlink is listened continuously

The messages sent by end-devices are delivered to all base stations within range, which makes delivery more reliable by adding redundancy (Mekki et al., 2018, p. 3). The difference between LoRa and LoRaWAN is that LoRa implements only the physical layer

of the protocol stack, while LoRaWAN also considers the upper layers of protocol stack and the system architecture (LoRa Alliance, 2015).

Sigfox is a network operator, which, along with its partners, provides end-to-end connectivity solution (U. Raza et al., 2017, p. 860). Sigfox offers data rate of only 100 bps or 600 bps (SigFox, 2018), supports payload length up to 12 bytes, and has a limitation of 4 downlink and 140 uplink messages per day (Mekki et al., 2018, p. 2), which makes it suitable for only very constrained applications. Sigfox has inexpensive antenna design, efficient bandwidth usage and low energy consumption (U. Raza et al., 2017, p. 860). As number downlink messages are limited, messages sent cannot be acknowledged, and therefore reliability is ensured by sending messages multiple times and using time and frequency diversity (Mekki et al., 2018, p. 2).

A short summary of LPWANs and cellular networks is presented in Table 9. 4G and 5G have very high theoretical speeds and low latencies compared to LPWANs. However, it should be emphasized that the theoretical speeds are rarely achievable. In addition, cellular networks have higher energy consumption than LPWANs (Mekki et al., 2018, p. 1). 4G's advantage over other networks is its availability: it is already deployed and highly used. Both LPWANs and Cellular networks allow the movement of the machine in a large area compared to short-range networks, which are presented in the following section. However, both networks are suitable for the overhead crane as its operational area is limited.

Table 9. Summary of LPWANs and cellular networks.

	4G	5G	NB-IoT	SigFox	LoRaWAN
Band	1.8/2.3/2.5/2.6/3.5 GHz[1]	1.8/2.6 & 30–300 GHz (expected) [1]	Depends on the network type**	433/868/ 915 MHz[2]	433/868/ 915 MHz[2]
Data rate	3Gbps DL 1.5Gbps UL	10 Gbps	250 kbps DL 20 kbps UL	600 bps DL 100 bps UL	50 kbps
Range	Depends on the base station type, 10 m – 50 km[3, 4]	< 1.7 km[5]	1 km– 10 km[2]	10 km– 40 km[2]	5 km– 20 km[2]
Latency*	Up to <5 ms, low	<1 ms, very low	50 ms – 850 ms[6], medium[2]	High[2]	Medium[2]
Energy consumption*	High[2]	-[7]	Medium[2]	Low[2]	Low[2]

* Relative

** LTE (1.8/2.3/2.5/2.6/3.5 GHz), GSM and GPRS (900/1800/1900) MHz (Cai & Goodman, 1997, p. 122).

[1] (Gandotra et al., 2017, p. 11)

[2] (Mekki et al., 2018, pp. 1, 3–4)

[3] (Wang & Chuang, 2015, p. 298)

[4] (Varshney, 2012, p. 38)

[5] (Roh et al., 2014, p. 111)

[6] (Soussi et al., 2018, p. 7)

[7] No data available

3.5.2 Short-range networks

Bluetooth works on unlicensed ISM 2.4 GHz frequency spectrum (Bluetooth SIG, 2018b) and by the year 2018, almost 4 billion devices with Bluetooth capability were shipped (Bluetooth SIG, 2018c). Bluetooth has two radio versions: Bluetooth Low Energy (LE), which is directed to low power devices and supports multiple data rates and transmission powers making it flexible, and Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR), which has higher data rates and more channels. Bluetooth LE also offers broadcast and mesh network topologies (Bluetooth SIG, 2018b), and supports device discovery (Collotta & Pau, 2015, p. 139). BLE is optimized for data transfer whereas BE/EDR is optimized for audio streaming (Bluetooth SIG, 2018d). The range of Bluetooth depends on transmit power and is about 15-30 meters (Lopez et al., 2013, p. 1353). However, higher ranges are achievable, and some commercial solutions claim to have a range of up to 500 meters. In addition, Bluetooth 5.0 should increase range fourfold compared to the older generations. (Bluetooth SIG, 2018a)

Wireless local area networks (WLANs) usually refer to IEEE 802.11 class of standards. These standards are also called as Wi-Fi and include, for example, 802.11a/b/g/n. (Kurose & Ross, 2013, pp. 552–553) The most interesting Wi-Fi standard in the context of this thesis is 802.11ah, which offers lower energy consumption and longer range (100 m – 1 km (Tian, Famaey & Latre, 2016, p. 1)) than other Wi-Fi standards (Sethi & Sarangi, 2017, p. 13). It works on sub-GHz frequency band (Tian, Deronne, et al., 2016, p. 49) while other Wi-Fi standards usually work either on 2.4 GHz or 5 GHz (5.1 GHz - 5.8 GHz) frequency bands (Kurose & Ross, 2013, p. 552). 802.11ha offers low data rates from 150 kbps to 8 Mbps (in addition, higher data rates up to 347 Mbps are achievable, but are not available in every continent as they require 16 MHz frequency band) (IEEE Standard 802.11ah-2016, 2017). In comparison, for example, 802.11ax allows very high data rates up to 9.6 Gbps (Khorov et al., 2018, p. 6). Because 802.11ah is a fairly new standard, there is a lack of devices supporting it. The benefits of Wi-Fi standards include IP-network compatibility, and power saving mechanism, which allows sleeping of a device lowering energy consumption (Tozlu et al., 2012, pp. 134, 136).

Z-Wave is a low power protocol "used for IoT communication, especially in smart homes and small commercial domains" (Al-Sarawi et al., 2017, p. 687). It was developed by Zensys (presently a division of Sigma Systems) and, currently, it is developed by Z-Wave Alliance. Z-Wave uses ISM 900 MHz frequency band and provides a data rate of 40 kbps but supports also 2.4 GHz frequency band, which allows higher data rates up to 200 kbps. The range is approximately 30m indoor and 100m outdoor. (Gomez & Paradells, 2010, p. 97) Z-Wave has two types of devices: slaves and controllers. Controllers are responsible for managing slaves and maintaining a table of a network topology for routing. Routing is based on source routing, in which the route is sent along with the packet. Z-Wave offers a reliable transmission by optional ACK messages. (Al-Fuqaha et al., 2015, p. 2360)

ZigBee is a low-cost, low-power communication standard, which works on top of IEEE 802.15.4 physical (PHY) and medium access control (MAC) layers (Zigbee Standards Organization, 2012, pp. 1–2). It is used for home automation and monitoring (Lennvall, Svensson & Hekland, 2008, p. 87). ZigBee works on both 868/915 MHz and 2.4 GHz frequency bands. The data rate depends on the used frequency band being 20 kb/s at lowest (868 MHz) and 250 kb/s at highest (2.4GHz). (Gomez & Paradells, 2010, pp. 95–96) The range is up to 75m - 100m indoor, up to 300m meters with line of sight, and up to 1km on sub-GHz frequency band (ZigBee Alliance, 2018). ZigBee supports three types

of network topologies: star, tree, and mesh. The mesh topology increases the reliability of the network via redundant paths. (Wang & Jiang, 2016, p. 2201) However, the lack of robustness of the technology is limiting its suitability for industrial applications (Lennvall et al., 2008, p. 88). There is also an IPv6-compatible version of ZigBee (Wang & Jiang, 2016, p. 2204).

WirelessHART (Highway Addressable Remote Transducer Protocol) is a wireless communication standard designed for process automation applications and industrial use (Wang & Jiang, 2016, p. 2200). It is developed by the HART Communication Foundation and was released in 2007 (Kim et al., 2008). The standard uses IEEE 802.15.4 at the physical (PHY) layer at a 2.4 GHz frequency band (Wang & Jiang, 2016, pp. 2200, 2205). The maximum data rate up to 250 kbps and range varies from 50 m indoor to 250 m outdoor (Qureshi & Hanan Abdullah, 2014, p. 1220). The protocol supports both star and mesh network topologies, but the mesh is preferred to ensure robustness and reliability. In addition, TDMA (Time Division Multiple Access) with CSMA (Carrier-sense Multiple Access) is used, which allows deterministic latency. (Wang & Jiang, 2016, pp. 2202, 2205) TDMA and pre-scheduled time slots reduce both collisions and energy consumption. As the protocol is designed for industrial use, the security of the protocol is at a high level and can't be disabled. (Lennvall et al., 2008, pp. 87–88)

Table 10 summarizes the properties of short-range networks from the above review. However, there is a lack of comprehensive comparison of short-range networks in the scientific literature. In addition, the existing technologies are constantly updated, and new technologies released. Thus, at the time a scientific article is published, it might be already outdated. For the above reasons, some of the information about latencies and energy consumption have been collected from non-scientific sources. Therefore, the values should be considered more as guidelines.

Short-range networks have a large variation in data rates as can be seen from Table 10. 802.11ah has the fastest data rate along with Bluetooth. However, the theoretical maximum speed of 802.11ah is not achievable in every continent. The ranges of the networks depend mostly on the used frequency band: with 900 MHz frequency band, the range is significantly longer than with 2.4 GHz. The only industrial protocol in this literature review is WirelessHART. Compared to other protocols, it is more robust and has both deterministic latency and built-in security. Therefore, it is the most suitable communication technology for use cases in which high predictability and security are required. However, the high latency of WirelessHART reduces its suitability for controlling machines.

The above review and Table 10 show that short-range networks have a large variation in their properties. Therefore, each of the networks has its own most suitable applications. The suitability of both short-range networks and LPWANs for the selected use cases are assessed in the following section.

3.5.3 Comparison

There are numerous aspects that are concerning the selection of communication technology such as data rate, latency, robustness, security, and energy consumption. In addition, some of the properties such as energy consumption are use case dependent. Furthermore, the lack of scientific papers with a comprehensive comparison of communication technologies makes the selection of the most suitable communication technology even more challenging. However, some comparisons are available. For example, Siekkinen et

al. (2012) found that BLE has lower energy consumption per bytes transferred than ZigBee.

Table 10. Summary of short-range networks.

	Bluetooth	Wi-Fi 802.11ah	Z-Wave	ZigBee	Wire-lessHART	Wi-Fi 802.11n
Band	2.4 GHz	900 MHz*	868 Mhz/ 908 Mhz & 2.4 Ghz*	900 MHz & 2.4 GHz*	2.4GHz	2.4 GHz & 5 GHz[1]
Data rate	2 Mbps (LE) 3 Mbps (EDR)[2]	150 kbps – 8 Mbps, up to 347 Mbps	40 kbps (900 MHz) 200 kbps (2.4 GHz)	20 kbps (868 MHz) - 250 kbps (2.4 GHz)	250 kbps	54 Mbps – 600 Mbps[1]
Range	15 m – 30 m (typi-cal), up to 500 m	100 m – 1000 m	30 m (in-door) 100 m(out-door)	75 m – 100 m (indoor, 2.4 GHz), up to 1 km (900 MHz)	50 m (in-door) 250 m (outdoor	100 m[1]
Latency	2.5 ms (LE)[3]	1.56 ms to 28.44 ms[4] / 59 ms to 1422 ms[5]	approx. 1000 ms[6]	20 ms[3]	approx. 2000 ms[7]	6.22 ms (2.4 GHz)[8] 0.9 ms (5 GHz)[8]
Energy consump-tion**	Low	Low	Medium	Medium	Medium	High
IP-compat-ible[9]	No	Yes	No	No	No	Yes

* The frequency band depends on the country

** Relative, information combined from: (Panasonic Industrial Company, 2008; Siekkinen et al., 2012; İnce et al., 2014; Mannion, 2017b)

[1] (İnce et al., 2014)

[2] (Bluetooth SIG, 2018b)

[3] (Mannion, 2017a)

[4] Simulated transmission time (Šljivo et al., 2018)

[5] Network delay (Šljivo et al., 2018)

[6] (Knight, 2006)

[7] Depends on superframe size (Petersen & Carlsen, 2009)

[8] Median (Grigorik, 2013)

[9] (Kim et al., 2008, p. 900; Kim, Choi & Rhee, 2015, p. 13; Gomez & Paradells, 2010, p. 95; Tozlu et al., 2012, p. 134)

Some of the communication technologies are IP-compatible, which might make deployment of the system easier as gateways are not needed. The availability of the network is also affecting the choice of the communication technology. For example, cellular technologies such as 4G and Wi-Fi are already widely deployed and used. In addition, the availability of devices and accessories is also an important factor. For example, Bluetooth and Wi-Fi are supported by almost any device/microcontroller compared to, for example, Z-Wave and ZigBee. However, support for ZigBee and Z-Wave can be added with external modules (Adafruit Industries, LLC, 2017).

None of the communication technologies is technically superior to each other, and the same use case can be implemented using various communication technologies. This might be the reason, why there are so many communication technologies available. There are also numerous other communication technologies available than the ones examined in this literature review, especially in the industrial field. For example, NFC was left out as its range is only in order of 10 cm (Want, 2011, p. 4) and RFID, because it is only suitable for reading static, pre-programmed data, instead of measurement data (Al-Sarawi et al., 2017, p. 686).

In both use cases, a short-range network is an option because the overhead crane is rather a static object as the movement range is a few tens of meters. For the first use case, in which the sensor data is used to control the machine, very low latency is required. Therefore, suitable options are 4G, the coming 5G, Bluetooth or 802.11ah/802.11n. However, all of these are technologies are also used by other devices, which might cause congestion. The congestion increases latency and slows down the data rate, which makes the behavior unpredictable. WirelessHART has otherwise suitable properties such as robustness and deterministic latency, but its latency is too high for controlling the crane. The choice for the first case is 802.11n in the 5Ghz frequency spectrum as it has the lowest latency. However, with 802.11n, the sensor node can't be battery operated because of the high energy consumption.

For the second use case, there is no single "the most suitable technology" as the requirements for the data rate and latency are not strict. Only Sigfox does not meet the requirements as the number of uplink messages is limited to 140 per day. In general, Sigfox is suitable for use cases in which the status of the machine is updated rather seldom instead of sending measurement data due to the small payload and restricted number of uplink messages. Wi-Fi (802.11n) is the preferred choice for the second use case due to easy implementation. It offers IP-compatibility and deploying a network is effortless. If low energy consumption is considered as the most important factor, Bluetooth is the recommended choice from short-range networks and LoRaWAN from LPWANs.

In general, if there are multiple sensors measuring at very high sample rates, only 4G, 5G, Wi-Fi or Bluetooth are able to transfer data at speeds high enough. 4G and 5G allow a free movement of the machine, while Wi-Fi and Bluetooth allow movement only at the very limited area (Wi-Fi 802.11ah maximum range is 1 km). 802.11ah would be a good choice in general as it has low energy consumption, high range, and high data rate but there are no devices available supporting it.

In this chapter, the communication needs of a digital twin were identified. In addition, application layer protocols and communication technologies were examined and their suitability for sensor data transmission was assessed through the selected use cases. The next chapter presents the requirements for a platform, which enables the management of sensors and sensor data transmission from physical twin to a digital twin in practice.

3.6 IoT platforms

To enable data collection from a physical twin in practice, a system for managing sensor nodes is required. Thus, this section presents a short review on existing IoT platforms, which allow the management of sensor nodes. The amount of IoT platforms, IoT related software, standards, and protocols is enormous. Therefore, presenting a comprehensive review of IoT platforms in out of the scope of this thesis. The literature review focused on platforms presented at the scientific papers, which might leave out recently published

platforms as well as some commercial platforms. The following properties, which are beneficial for the platform enabling sensor node management, were considered on the review of existing IoT platforms:

- Possibility to change measurement settings
- Support for multiple application layer protocols
- Support for multiple sensor types
- Easy addition of new sensor types
- Free and open-source

There exist several IoT platforms with various focus points. IoT platforms can be divided into the following three categories (da Cruz et al., 2018, p. 875):

1) Device management
2) Application management, in which the platform is used for developing applications
3) Application enablement, in which the platform allows developing external applications by, for example, providing the sensor data

Da Cruz (2018, p. 875) identified the following device management concentrated platforms (*=open-source): Alljoyn*, Artik Cloud, Carriots (currently Altair SmartCore), IoTivity*, Linksmart*, Losant, OpenIoT*, Stack4Things*, Telit IoT Platform, WSO2 IoT server*, Webinos* and Xively. As can be seen, the number of available platforms is overwhelming. In addition, new platforms are constantly released and the development of older ones are stopped: For example, the latest commit to OpenIot platform was made over three years ago (GitHub, Inc., 2019c). The problem with open-source platforms created as a part of research project seems to be that after the research project has ended also the development of the platform ceases.

The platforms usually offer the same functionalities, but the variety of their implementations makes the comparison of platforms difficult (Guth et al., 2016, p. 1). A few paradigms for implementation of the device management can be found from the scientific literature. For example, El-Mougy et al. (2015) present a Software-defined Networking based method (SDN). Simplified, SDN separates the data plane and control plane of network and therefore allows better control of the network (Benzekki, El Fergougui & Elbelrhiti Elalaoui, 2016, pp. 5803–5804). An SDN-based architecture would allow configuration and programming of sensors wirelessly. However, the current hardware of sensors does not support this method. (El-Mougy et al., 2015)

Vresk & Cavrak (2016) present a microservices based architecture for IoT platform, in which the platform consists of small interconnected software components called microservices to enhance the scalability of the system. An edge-computing based approach called transparent computing is presented by Ren, Guo & Zhang (2017). This approach allows IoT devices to download updates from the cloud, increases the scalability of the system and offers real-time and context-aware data processing. Next, two implementations of IoT platforms found in the scientific literature are presented.

Lazarescu (2015) developed a platform for WSN (Wireless Sensor Network). The platform was designed for detecting wildfires in the rural area. It uses the 433 MHz ISM band and a star topology for communication. The sensor nodes use ATtiny microcontroller and gateways ATmega324P microcontroller. However, the platform is lacking the possibility to control measurement settings, which is one of the key features, which make the system suitable for the data collection from a physical twin.

Lin et. al (2017) present an IoT platform called IoTtalk. It uses a device called MorSensor as its sensor node. The platform allows “plug-n-play” addition of new sensors to the system: after a new sensor is attached to the MorSensor device, the sensor type is recognized, and it is added to the platform’s database. IoTtalk allows control of actuators attached to MorSensors. The inputs (data produced by sensors) can be linked to the output devices (actuators such as display or fan) from the GUI of the platform. The platform is open-sourced, but documentation is poor or missing (GitHub, Inc., 2019a).

In this chapter, the communication needs of a digital twin were identified. In addition, application layer protocols and communication technologies were examined and their suitability for sensor data transmission was assessed through the selected use cases. Finally, a short review on existing IoT platforms were presented. The next chapter presents the requirements for a platform, which enables the management of sensors and sensor data transmission from physical twin to a digital twin in practice.

4 Sensor configurator platform

A platform for the management of sensor nodes was developed as a part of this thesis. The platform narrows the gap between the concept of a digital twin and its realization by allowing the sensor data transmission from a physical twin to a digital twin. This chapter presents requirements for the developed platform, called the Sensor Configurator Platform (SCP). In addition, the hardware and software used by the platform are described.

4.1 Requirements

The purpose of the developed platform is to allow the management of the sensor nodes remotely over the internet and, thus, allow the data collection in the context of a digital twin. The management includes changing measurements settings such as sample rate or sensitivity and adding/removing sensors. In the previous chapter, the most suitable application layer protocols and communication technologies for the sensor data transmission from a physical twin to a digital twin were compared. The results indicate that MQTT and DDS as well as Wi-Fi (802.11n) should be supported by the platform. In addition, support for other application layer protocols and communication technologies is a desirable property to make the platform suitable for various use cases. For the same reason, multiple sensor types should be supported.

Currently available IoT platforms usually offer numerous properties from data processing, visualization, and storing to acting as a platform for apps. However, in the case of a digital twin these functionalities can be implemented by the other (sub)systems of a digital twin. Therefore, the developed platform should focus only on the management of sensor nodes. This allows making the platform light-weight and simple. An interface, which subsystems of a digital twin can use to modify the measurement settings, is required. This interface should be a REST API because a REST API is an easy-to-use and a widely adopted way of implementing interfaces.

Existing IoT platforms concentrate on enabling the communication of the sensor node, but the implementation of the measurement loop and fetching data from the sensor has to be programmed by the user. To facilitate this configuration process of sensors, the platform should automatically generate the code for sensor nodes. This allows the use of the platform without prior knowledge of microcontrollers and their programming.

The requirements for a platform enabling the management of sensors and sensor data transmission are presented in Table 11. The requirements are divided into demands and wishes to indicate the importance of the requirement to the functionality of the platform. The requirements marked as demands were emphasized in the development of the platform.

4.2 Hardware

The hardware of the system implemented consists of sensors, microcontrollers, and Raspberry PIs. A sensor node consists of a microcontroller and, currently, a single sensor. Sensors use I^2C bus to communicate with microcontrollers. The platform currently supports the following sensors:

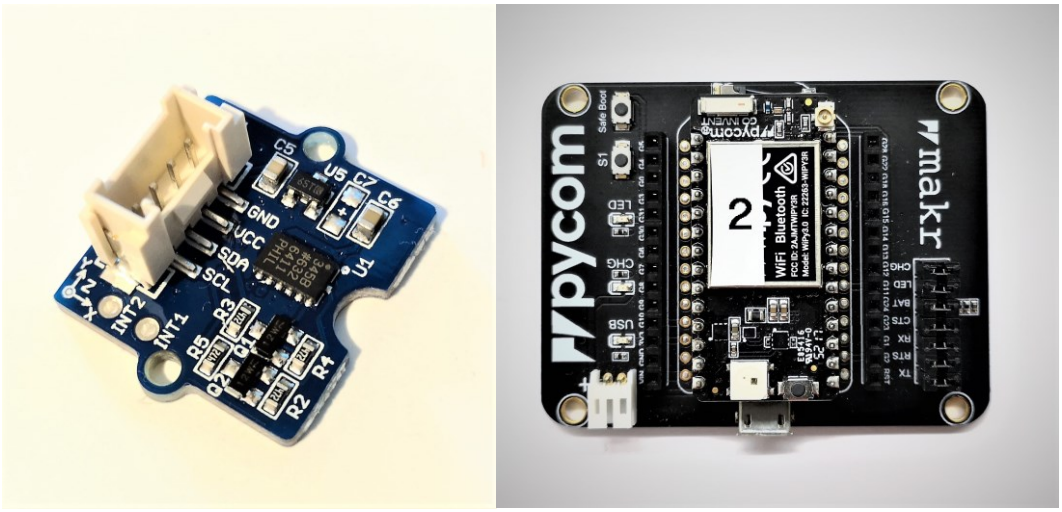
- ADXL345, a three-axis accelerometer (Analog Devices, Inc., 2019) shown in Figure 24a.
- LIS3DSH, a three-axis accelerometer (STMicroelectronics, 2019).
- Seeed Grove I2C ADC, a 12-bit analog to digital converter based on ADC121C021 (Seeed Technology Co., Ltd., 2018).

The microcontrollers used are manufactured by Pycom. They use Espressif ESP32 chipset and can be programmed with MicroPython (Pycom Ltd., 2017), which is an implementation of Python 3 for microcontrollers (George Robotics Limited, 2018). All of the boards support Wi-Fi and Bluetooth, but models with the support of LoRa, SigFox and NB-IoT are also available (Pycom Ltd., 2018). Pycom also offers additional tools such as Pymakr (Pycom Ltd., 2019) for easier programming. Figure 24b shows a WiPy microcontroller with an extension board. Sensor configurator and data server are hosted on Raspberry PI model 3 B+s.

Table 11. The requirement list for the sensor configurator platform.

Requirement	Type*
Communication	
- Supports Wi-Fi	D
- Supports at least one other communication technology	W
- Adding new communication technologies is easy	D
- Supports MQTT	D
- Supports DDS	D
- Support other application layer protocols	W
- Adding new protocols is easy	W
- Support for sending data directly to MindSphere	W
Functionalities	
- Remote configuration of sensors	D
- Configuration over internet	D
- Possibility to measure bursts	W
- Support for I2C bus sensors	D
- Adding new sensors is easy	W
Configurable parameters	
- Sample rate	D
- Sensitivity	W
- Wi-Fi settings (SSID, key, auth type)	D
- Data sent rate	W
- Burst length and rate	W
User interface	
- Easy to use	W
- Data visualization	W
- Possibility to download data	W
Sensor nodes	
- Low energy consumption	W
- Led lights indicating the status	W
- Support for multiple communication technologies	W
API	
- Sensors can be added and deleted	D
- Sensors can be modified	D
- HTTP Basic authentication	D
- Token-based authentication	W

* D = Demand, W = Wish



(a) (b)

Figure 24. ADXL345 3-axis accelerometer (a) and PyCom WiPy 3.0 microcontroller with Expansion Board 3.0 (b).

4.3 Software

MicroPython is used for programming microcontrollers. The Sensor Configurator Platform and data server use Django, which is an open-source Python Web framework. Django was chosen because it allows a quick creation and development of websites. In addition, it has numerous built-in features such as user authentication and administration page. (Django Software Foundation, 2019) There are also several plugins available for Django. For example, *Django REST framework* was used to create REST APIs (Django REST framework, 2019) and *Simple JWT* for authentication (Sanders, 2018). In this context REST API (Representational State Transfer Application Programming Interface) describes an interface that other systems can use to communicate with the sensor configurator platform. REST APIs are commonly used, application developers are familiar with them, and they are usually easy to use. SQLite database is used for both the sensor configurator platform and the data server.

The following libraries/frameworks were used at the front-end of the SCP:

- Bootstrap, which an open-source framework for creating responsive web UIs (Bootstrap, 2019).
- jQuery, a JavaScript library for easier "HTML document traversal and manipulation, event handling, animation, and Ajax." (The jQuery Foundation, 2019)
- Plotly.js, an open-source JavaScript library for making charts (Plotly, 2018).
- Handsontable, a JavaScript component for creating spreadsheets (Handsoncode, 2019).

Adafruit IO cloud service was used to implement MQTT communication. It offers data visualization (Figure 25) and a possibility to add triggers to perform certain action based on data received. (Rubell, 2018) In addition, it has a free version available with limited properties (such as 30 messages per minute) (Adafruit Industries, LLC, 2019). The properties of the free version are sufficient for the second use case. However, for the first use case, the message rate per minute is too low.

This chapter presented requirements for a platform allowing sensor management and sensor data transmission. Based on these requirements, a sensor configurator platform was

developed. The platform, called the Sensor Configurator Platform (SCP), is presented in more detail in the following chapter.

Figure 25. An example of data visualization by Adafruit IO cloud service with randomly generated data

5 Results

This chapter introduces the developed platform, protocol, and data server for sensor data transmission. In addition, the results of the user tests conducted for the platform are presented.

5.1 Sensor configurator platform

The purpose of the Sensor Configurator Platform is to allow management of sensor nodes attached to a physical twin and enable their data transmission. The management includes adding/removing sensor nodes as well as modification of their measurement and data transmission settings. The platform allows modification of a sensor node's settings remotely over the Internet. Data transmission is enabled by offering a coding-free configuration of sensor nodes via a web user interface (WUI) shown in Figure 26 and offering several options to data transmission such as choice between multiple application layer protocols. The key features of the developed platform are:

- Possibility to change a sensor nodes' settings including measurement settings and data transmission settings remotely over the Internet
- Access to functionalities via REST API
- Adding new sensor nodes is coding-free
- Platform's architecture supports adding new sensor types, new communication technologies and application layer protocols
- Support for multiple application layer protocols

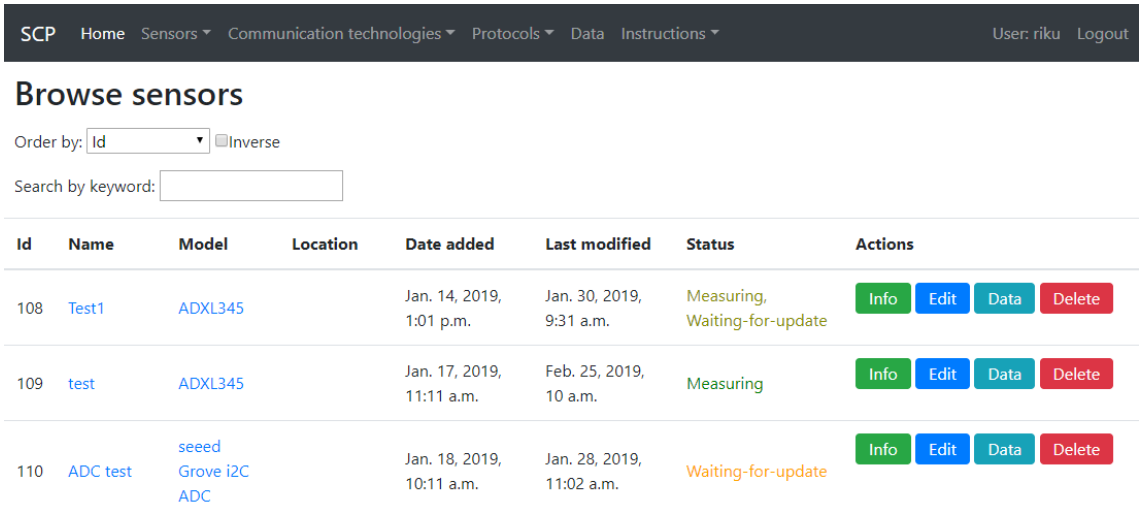


Figure 26. Web user interface's "Browse sensors" view.

The overall picture of the communication between the platform and other entities is presented in Figure 27. The user manages sensors via the web user interface, whereas other systems such as external systems or systems a digital twin consists of use the REST API of the platform. The SCP does not store or have access to the data sensor nodes transmit. Instead, data is sent to separate data storage, which might be an external system or a part of a digital twin. Entities interested in the measurement data use the interface of the data storage to fetch the data.

Next, the process of updating a sensor node's settings is presented step-by-step to demonstrate the operation of the platform. First, the settings of a sensor node are modified via WUI or API and the sensor configurator generates a MicroPython file (Appendix 1) based on these settings. If SDTP (Sensor Data Transmission Protocol), which is presented in

the next section, is used, the information of an available update is sent to the data server via REST API using JWT authentication. Sensor nodes can get information about the available update in two ways:

- Sensor always asks updates periodically (the time period is freely configurable) from sensor configurator with an HTTP request.
- Sensor gets information from the data server, after which the update is asked from the given IP address with an HTTP request.

The first option does not require any connection between the Sensor Configurator Platform and the data server, which is one of the main design principles of the system: sensor configurator platform should work as an independent system without any links to other systems. The second option was implemented, however, as it is more efficient: the sensor node needs to open a connection only when sending data because it gets information of available updates from a data server.

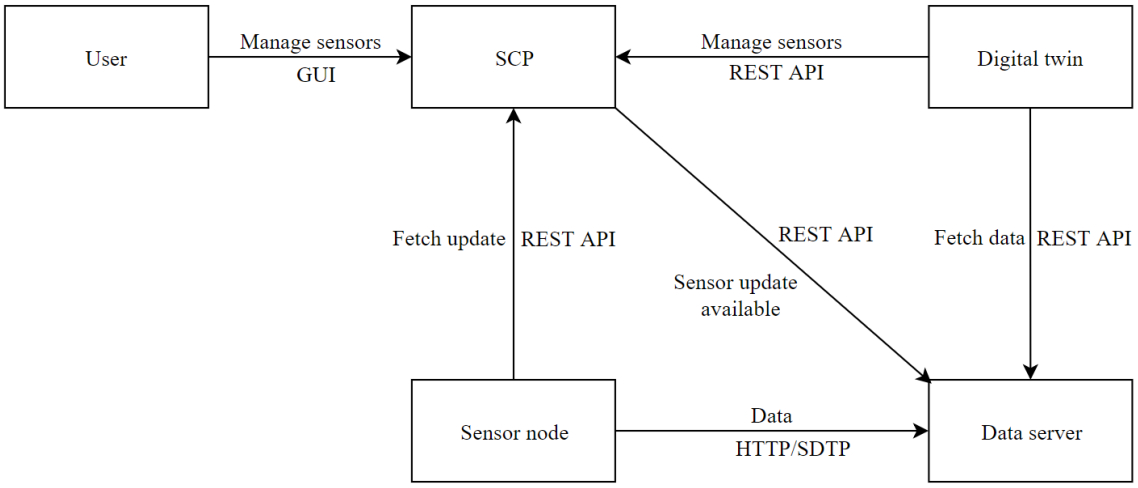


Figure 27. Communication between the SCP and other entities.

If there is an update available when an update is asked, the sensor configurator responds with an HTTP response containing the generated MicroPython file in the payload. After the sensor node has received a new MicroPython file, the file is written to the file system and microcontroller reboots. The boot.py, which is run on every start-up, removes the old *main.py* file and renames the new file as *main.py*. After each boot-up, a sensor node asks for updates. When an update is asked, the current software version is passed to the platform. With that information, the platform knows, if the sensor has received the latest update and can change its status from "Waiting-for-update" or "Measuring, Waiting-for-update" to "Measuring".

A sensor node can currently use the following application layer protocols to send the measurement data: SDTP, HTTP, and MQTT. When using HTTP or MQTT, the data is encoded as JSON, shown in Figure 28, and with SDTP the data is sent as bit formatted. A data storage is responsible for making the data available to systems a digital twin consists of or to external systems. The data server implementation used in this thesis offers a REST API to access the data. However, the design of an interface for fetching the data is up to the developer of the data server.

The key feature of the sensor configurator platform is the possibility to modify the settings of sensor nodes remotely over the Internet. The general configurable settings are shown in Table 12.

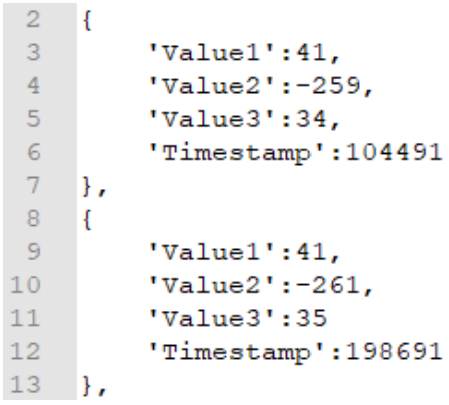


Figure 28. JSON encoded data is used when measurement data is sent with HTTP.

Optionally, a short description and location of a sensor node can also be given. In addition, communication technology can be chosen. However, only Wi-Fi is currently implemented. The configurable Wi-Fi settings are listed in Table 13.

Table 12. Configurable sensor node settings.

Setting	Description/additional information	Example value
Data server IP address	The sensor node sends data to this IP address	86.70.113.151:2500
Update check IP address	The sensor node asks updates from this IP address	86.70.113.151:8000
Update check limit	The time interval between consecutive update checks	3600 (s)
Sensor model	Currently supported sensors: ADXL345, LIS3DSH, Seeed Grove I2C ADC	ADXL345
Sample rate	Maximum sample rate depends on the application layer protocol	100 Hz
Sensitivity	Depends on the sensor model	+-2g
Burst length	The length of burst in seconds. Can be set to 0 for continuous measurement	5.0 (s)
Burst rate	The time interval between consecutive bursts	3.0 (s)
Data send rate	The time interval between data transmissions to a data server. If set to 0, data is sent immediately	10 (s)
Connection close limit	Adjusts the time period after connection to a data server closed if new data is not sent	3 (s)
Network close limit	Adjusts the time period after connection to network is closed if new data is not sent	30 (s)

Table 13. Configurable Wi-Fi settings.

Setting	Description/additional information	Example value
SSID	Service set identifier	TP_Link_Arch
Security	Options: Nothing, WEP, WPA, WPA2, WPA2_ENT	WPA2
Username	Optional, depends on *Security* setting	test_user
Key	Optional, depends on *Security* setting	password1

Application layer protocol is also configurable. Three options are currently available: SDTP, HTTP, and MQTT. For SDTP, there are no configurable settings and, for HTTP,

the path the data is sent can be modified. MQTT has the following configurable settings presented in Table 14.

Table 14. Configurable settings for MQTT.

Setting	Description/additional information	Example value
User	Username for the broker	test_user
Key	Token used for authentication	b401jdlfpep3r59c2a6241dk258bf48
Topic	Topic to which data is published	test_user/feeds/topic_name
Data server url	Broker url	io.adafruit.com
Port	Port used	1883

The admin page offers an easy user interface for managing users (Figure 29). Django's built-in user authentication system is used for user authentication. Three authentication levels are implemented:

- User, who can view sensor nodes details
- Manager, who can add, modify and remove sensor nodes
- Admin, who can manage users and add new sensor types

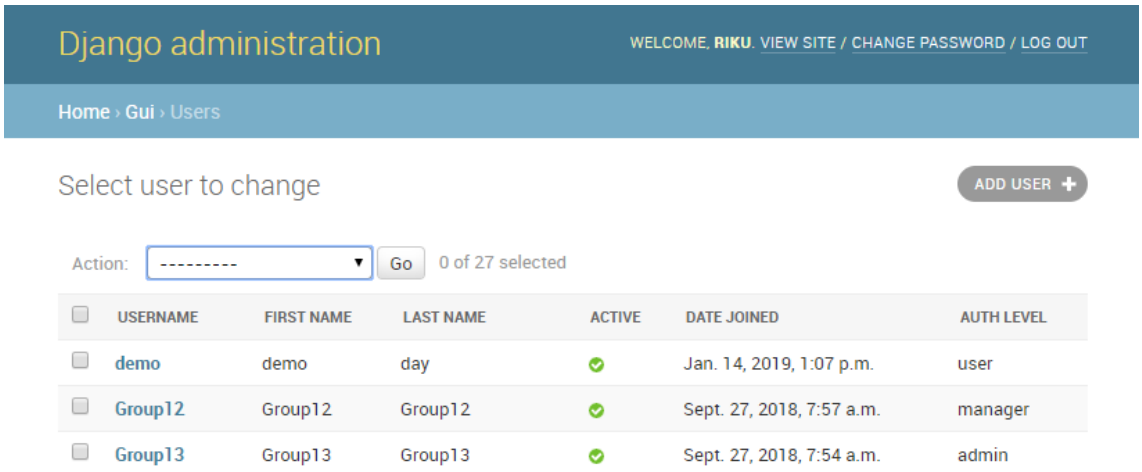


Figure 29. Django admin view for managing users (for clarity, email, id, and password columns are removed).

In addition to user management, the admin page is used for adding new sensor types. Next, this process is presented in more detail. First, a new sensor type instance is created to the database. This instance includes I^2C address, description, and an optional data handling function as a python script. A script is required if additional bit operations such as bit shifts are needed to convert bit formatted measurement data to numbers. Next, sample rate objects are created. Each sample rate supported by the sensor type requires its own sample rate object, which is then linked to the sensor type. Sample rate object includes the write value pairs consisting of the address and the value to be written, which are needed to configure sensor, and read value pairs, which consist of the address and how many bytes are read from the address, for reading the data. These value pairs can be found from the sensor's manual. Finally, sensitivity objects, which work similar to sample rate objects are created. The value pair based method used for configuration of a sensor and reading the data allows completely coding free way of adding sensors if bit operations are not required.

A web user interface is implemented for easy management of the sensor nodes. The user interface supports adding, configuring and removing sensor nodes. In addition, it allows

browsing sensor nodes monitoring their statuses and checking the current settings of the nodes. For demoing purposes, a few additional features to user interface were implemented. These features can be used, if the sensor node uses SDTP as an application layer protocol and sends data to the implemented data server (introduced in the section 5.3). These additional features include data visualization (Figure 30), inspecting the data as a table and downloading the data as a CSV-file.

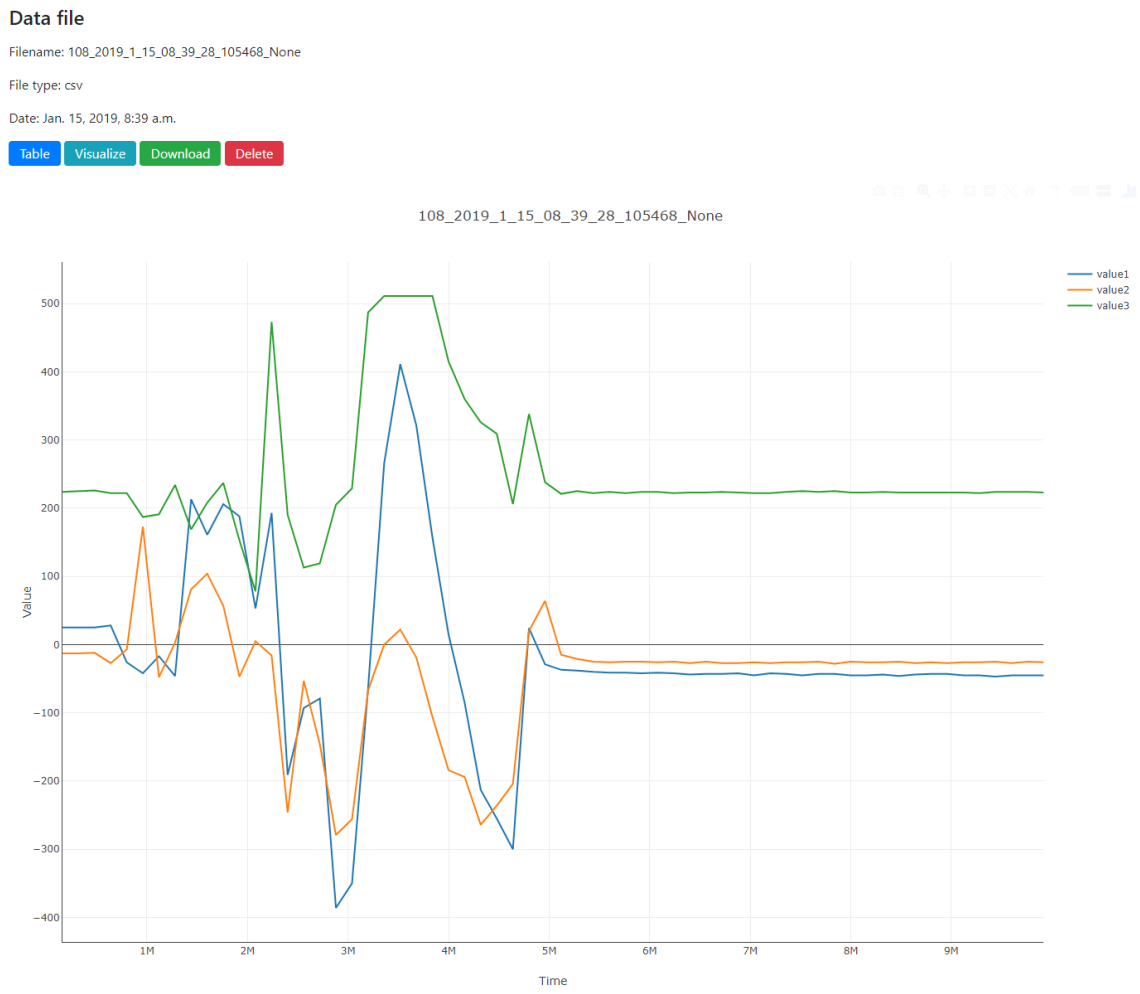


Figure 30. Data visualization of three-axis accelerometer ADXL345.

REST API offers the same functionalities as the web user interface and admin page, except user management. The API root view, which is generated by Django REST framework, shows visually the available resources (Figure 31). API allows, for example, browsing sensors nodes (Figure 32) and modification of their settings. Supported authentication methods for the API are HTTP basic authentication and JSON Web Token (JWT) authentication. In HTTP basic authentication username and password are used to authenticate the user. When using JWT (JSON Web Token) authentication, first a string called token is generated by the server and given to the client. After that, the client passes the token along with requests to API, which uses the token to verify user identity.

The maximum sample rate was tested with ADXL345 and Seeed Grove I2C ADC sensors. Data sent rate was set to 10 seconds, and the connection was closed after each data transfer. With both sensor types and SDTP, the maximum sample rate is 200 Hz. With HTTP, the maximum sample rate is 12.5 Hz, which indicates that the processing power of the microcontroller is limiting the maximum sample rate. The maximum sample rate

with MQTT could not be measured as the free version of the broker limited the sample rate.


```
HTTP 200 OK
Allow: GET, HEAD, OPTIONS
Content-Type: application/json
Vary: Accept

{
    "sensors": "http://86.50.143.154:8000/api/v1.0/sensors/",
    "models": "http://86.50.143.154:8000/api/v1.0/models/",
    "wlans": "http://86.50.143.154:8000/api/v1.0/wlans/",
    "nb-iots": "http://86.50.143.154:8000/api/v1.0/nb-iots/",
    "http": "http://86.50.143.154:8000/api/v1.0/http/",
    "https": "http://86.50.143.154:8000/api/v1.0/https/",
    "lwdtp": "http://86.50.143.154:8000/api/v1.0/lwdtp/",
    "mqtt": "http://86.50.143.154:8000/api/v1.0/mqtt/",
    "samplerates": "http://86.50.143.154:8000/api/v1.0/samplerates/",
    "sensitivitys": "http://86.50.143.154:8000/api/v1.0/sensitivitys/",
    "valuepairs": "http://86.50.143.154:8000/api/v1.0/valuepairs/"
}
```


Figure 31. API Root view generated by Django REST Framework.


```
HTTP 200 OK
Allow: GET, POST, HEAD, OPTIONS
Content-Type: application/json
Vary: Accept

[
    {
        "sensor_id": 108,
        "url": "http://86.50.143.154:8000/api/v1.0/sensors/108/",
        "sensor_name": "Test1",
        "model": "http://86.50.143.154:8000/api/v1.0/models/ADXL345/",
        "status": 2,
        "description": "",
        "location": "",
        "sensor_key": "vTdD3bkY9fXPHXvBqJjC",
        "sample_rate": "http://86.50.143.154:8000/api/v1.0/samplerates/9/",
        "sensitivity": "http://86.50.143.154:8000/api/v1.0/sensitivitys/2/",
        "data_send_rate": 10.0,
        "burst_length": 2.1,
        "burst_rate": 2.2,
        "connection_close_limit": 3.0,
        "network_close_limit": 30.0,
        "update_check_limit": 60.0,
        "update_check_ip_address": "86.50.143.154:8000",
        "data_server_ip_address": "86.50.143.154:2500",
        "communication_object": "http://86.50.143.154:8000/api/v1.0/wlans/1/",
        "protocol_object": "http://86.50.143.154:8000/api/v1.0/lwdtp/2/"
    },
    {
        "sensor_id": 109,
        "url": "http://86.50.143.154:8000/api/v1.0/sensors/109/",
        "sensor_name": "test",
        "model": "http://86.50.143.154:8000/api/v1.0/models/seeed%20Grove%20i2C%20ADC/",
```


Figure 32. The list of sensors provided by API visualized by Django REST Framework.

5.2 Sensor Data Transmission Protocol

For the communication between sensor nodes and data server, a new protocol was developed. In this thesis, it is called Sensor Data Transmission Protocol (SDTP). The purpose of the protocol is to enable lightweight two-way communication between sensor nodes and data server and allow high sample rates. High sample rates are also achievable with other application layer protocols, but as JSON encoding used with HTTP and the broker used with MQTT limited the sample rates there was a need for a new protocol. With SDTP, data is not processed by the microcontroller. Instead, it is transferred as raw and bit formatted to the data server. This allows a higher continuous sample rate, as the processing power of the microcontroller is not limiting the transmission rate. Apart from data transmission, SDTP is a text-based protocol and uses ASCII encoding. It runs on top of a reliable transport layer protocol, namely TCP. The conversation between the data server and the node is shown in Figure 33 below.

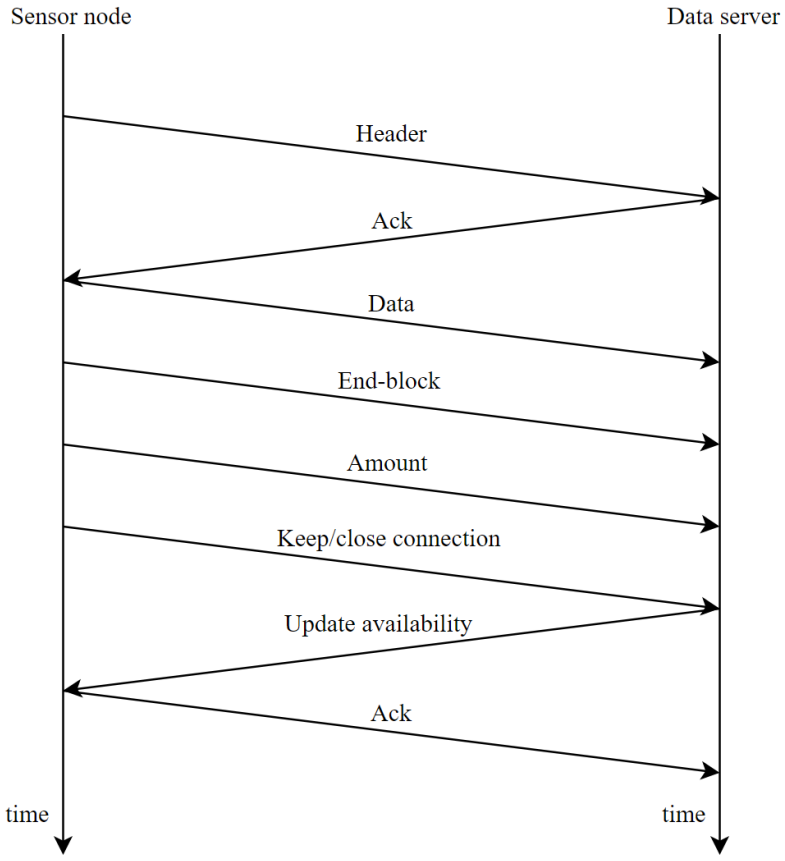


Figure 33. The conversation between a sensor node and a data server (Ack = Acknowledgment).

The header block contains the sensor's unique identifier and key, format string, and time stamp, which is the start time of the measurement. The format string indicates the data format as a string, in which the last letter indicates the format of time in microseconds from the beginning of the measurement and other letters the format of measured values. For example, "<hhhL" (= three times short integer and unsigned long integer with little-endian byte order). The data server responds with an acknowledge message to the header and starts listening data. After the measurement data is sent, an end-block and the number of bytes transferred are sent as long unsigned integer. Next, the sensor node either sends *keep connection* or *close connection*. Data server responds with update availability. If there is an update available, an IP address, where the update is located, is passed along with a response. Finally, the sensor node sends an acknowledge message.

Example messages sent in conversation:

- Header: "BEGIN: 6; 1234; <hhhL; (2017, 2, 28, 10, 30, 0, 0, 0)"
- Ack: “OK”
- Data: 0xE70x790x650x00013815 (as hexadecimal)
- End-block: “END”
- Amount: 12000
- Keep/close connection: “KEEP” or “CLSE”
- Update availability: “UPDATE: 86.50.143.154:8000” or “UPTODATE”

5.3 Data server

A distinct data server supporting SDTP was implemented to allow faster sample rates. The developed data server offers a REST API interface for accessing the data, which is also used by the SCP to fetch data for data visualization, and other additional features. The API uses similar authentication methods as the Sensor configurator platform, namely HTTP Basic and JWT authentication. It allows browsing the data files produced by sensors and downloading them as a CSV file. The API is also used by the SCP to fetch the data. The API root view generated by Django REST Framework is shown in Figure 34. The data produced by sensors is stored as text files.

```
HTTP 200 OK
Allow: GET, HEAD, OPTIONS
Content-Type: application/json
Vary: Accept

{
    "sensors": "http://86.50.143.154:2501/api/v1.0/sensors/",
    "datafiles": "http://86.50.143.154:2501/api/v1.0/datafiles/"
}
```

Figure 34. The data server's API Root view.

5.4 User test

A user test was arranged to assess the ease of use of the developed platform, which was one of its main design criteria. 26 students from technical universities around Europe participated in the user test. 22 of the participants answered to the feedback form. Their fields of study are listed in Table 15. 45 % of the respondents had used microcontrollers before this user test and 9% of them a system, which resembled the sensor configurator platform. The task given was to add a new sensor to the system, and it was executed in groups of two. The instructions given can be found in Appendix 2. The test setup contained a microcontroller attached to an expansion board, ADXL345 sensor, and cables shown in Figure 35. The time limit for finishing the task was roughly 60 minutes. Finally, feedback was collected using Google Forms.

73% of the respondents managed to accomplish the task given even though there were technical problems with the system. 73% of the respondents also needed to ask for help during the user test. Despite this, the Sensor Configurator Platform was considered easy to use (Figure 36). In addition, most of the problems (Figure 37) encountered by participants, were related to connecting the computer to the microcontroller via Wi-Fi and moving initial files to the microcontroller, which are actually more related to the microcontroller’s software than the sensor configurator itself. All of the respondents found the platform useful and 73% of them would use a system like it in the future. All questions and answers can be found in Appendix 3.

Table 15. The fields of study of the participants.

Field of study	No. of students
Applied Mathematics	1
Automatics and robotics	1
Bioengineering	1
Civil Engineering	1
Computer engineering	2
Electromechanical engineering, Energy	1
Engineering	2
Engineering physics	1
Industrial Design and Product Development	1
Industrial Engineering and Management	1
Information Technologies	1
Management	1
Mathematics	2
Mechanical Engineering	5
Mechatronic Engineering	1

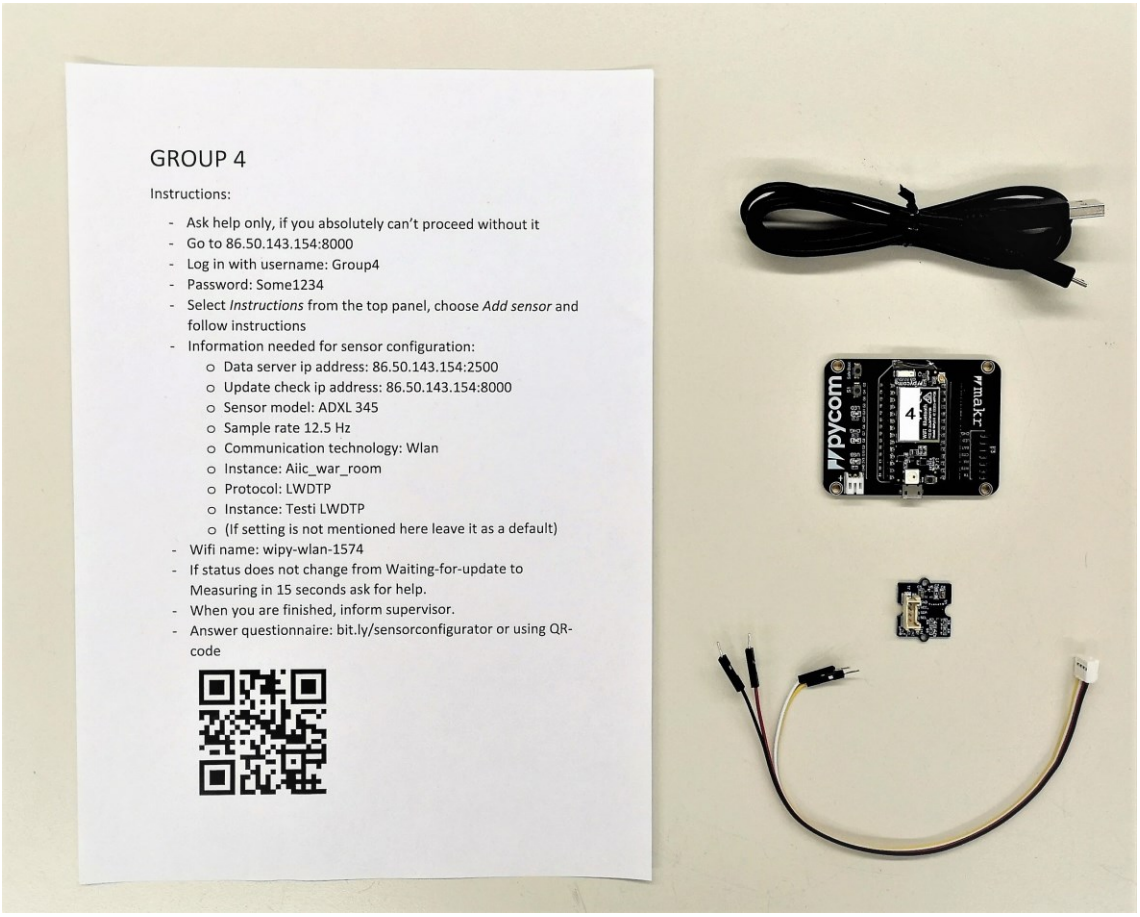


Figure 35. A test setup for the user tests.

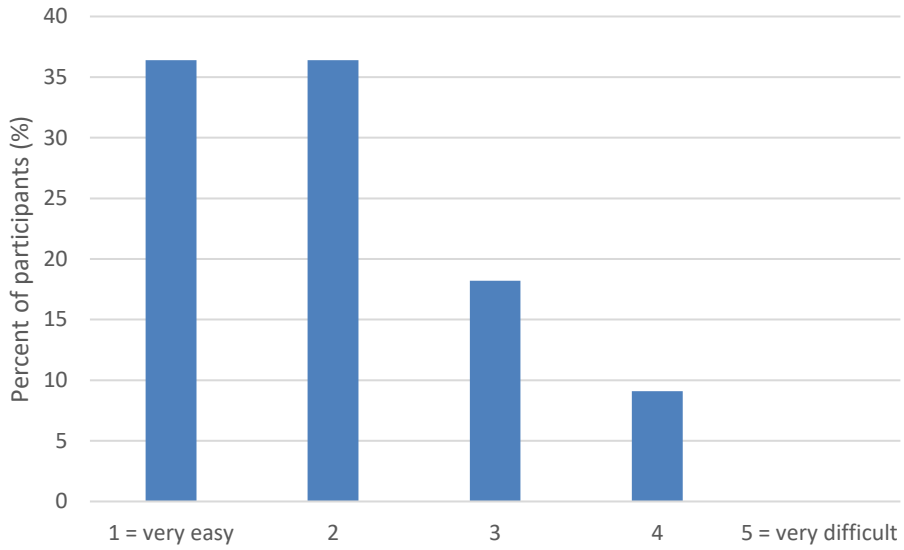


Figure 36. Ease of use of the system assessed by the respondents.

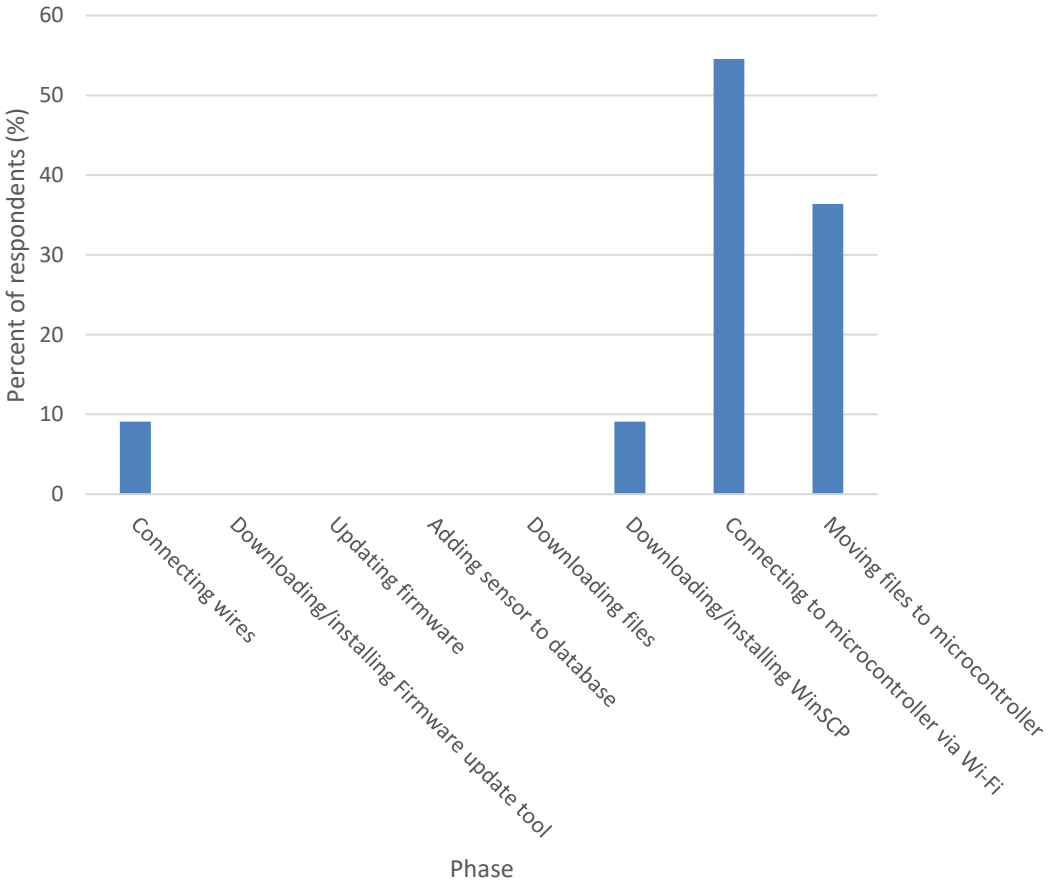


Figure 37. Problems encountered by respondents, broken by topics.

6 Discussion

The developed platform is a single ready-to-use system for a set of linked systems a digital twin consists of and allows data transmission from a physical twin to a digital twin. It allows easy addition of new sensor nodes to a physical twin, their remote management and data transmission using the most suitable standards. Therefore, the platform narrows the gap between the concept of a digital twin and its realization. The platform offers a REST API that the other subsystems of a digital twin can use to manage sensors remotely. In addition, the platform has a web user interface, which allows its use by a human operator.

Because the platform allows easy addition, configuration and management of sensor nodes, it can also be used outside the context of a digital twin. For example, the platform enables conducting simple measurement tasks in the laboratory and it can be used in teaching to demonstrate a measurement system. In student projects, the platform allows students to focus on the processing of the data instead of collecting it.

This chapter considers the future development areas of the platform and whether the developed platform fulfills the requirements set for it. In addition, recommendations for the most suitable application layer protocols and communication technologies for transmitting the measurement data from a physical twin to a digital twin based on the literature review are presented. The concept of a digital twin is also discussed. Finally, the significance of the platform and this thesis is evaluated in the context of a digital twin and DigiTwin project.

6.1 Sensor configurator platform

The developed sensor configurator platform narrows the gap between the concept of a digital twin and its realization by enabling the sensor data transmission. The transmission is allowed by easy addition, configuration and management of sensor nodes. In this section, the developed platform is assessed by examining whether it fulfills the requirements given in Table 11. Thereafter, the limitations and further development needs of the platform are presented.

The Sensor Configurator Platform fulfills all demands, except support for DDS, given in the requirement list (Table 11). DDS wasn't implemented because there is not a micropython library available and implementing a new library is out of the scope of this thesis. The demand for easiness of use was verified by means of user tests. The user test, which results are presented in chapter 5.4, indicated that the platform is easy to use even without prior knowledge of microcontrollers. Users also found the platform useful and, surprisingly, most of the users could contribute to this kind of platform if it was an open-source project.

Almost every wish was also fulfilled. Only the following wishes weren't accomplished:

- The connection to Siemens MindSphere. This wish couldn't be implemented, because the implementation of authentication and the process of creating new sensor/device instances to MindSphere was challenging.
- The support for multiple communication technologies. The wish of multiple communication technologies was discarded because Wi-Fi is suitable for most of the use cases. The initial plan was to add also support for NB-IoT. However, when the microcontroller's firmware was updated to enable the NB-IoT connection, the whole microcontroller became unresponsive.

- Low energy consumption. The low energy consumption could not be verified because there were problems with the power supply of the microcontrollers.

These unfulfilled wishes will be implemented in the next phase of the development of the platform.

Even though the platform is fully functional, there are several areas for improvement. Currently, the user management of the platform does not allow restricting the visibility of sensor nodes: every sensor node can be seen by every user. Basically, this means that to reduce visibility each user group of the system should have their own instance of the platform running on the server. Another limitation is the support for only Pycom's microcontrollers. However, the microcontrollers are based on general ESP32, and the MicroPython-file generated have only one Pycom specific functionality: flashing of led lights indicating the status of the board. One of the future development targets is to add support for several microcontrollers and allow generating code in other languages such as C and Arduino. At the moment, a microcontroller needs to be able to perform an HTTP request to fetch updates from the platform. Therefore, a microcontroller needs to be IP-compatible, which prevents the use of very constrained devices. Those devices would need a gateway for the Internet connection.

Microcontrollers use their internal memory to store the data read from the sensors. This restricts the time interval sensor can measure without forwarding data to the data server as the available memory is only in order of two megabytes. However, support for saving data to a memory card can be added in the future as the expansion boards used with microcontrollers have a slot for microSD card.

The CPU performance of the microcontroller limits the sample rate. Currently, the maximum sample rate is in order of 200 Hz with SDTP and 10Hz with HTTP. However, the used sensors are capable of sample rates over 1000 Hz. As can be seen from the HTTP sample rates, the microcontroller should not perform any processing of data (in this case, converting bit formatted data into integers and constructing JSON). If higher data rates, for example, with HTTP are required, edge computing could be used. With edge computing, the measurement data could be sent as a raw bit format data to a gateway, which could convert it to a JSON format and forward the data as an HTTP request to the data server.

Configurable settings presented in Table 12 cover the requirements for the management of a sensor node. However, the possibility to add threshold values to trigger certain actions could be added in the future. For example, if the value of temperature rises over a certain limit, a warning message could be sent to a certain IP address.

Currently, the platform uses an SQLite database, which does not support concurrent writing operations (Owens, 2006, p. 12). Therefore, if the platform is used by a large number of users and sensor nodes, the database should be changed. However, the write operations are quite rare in the sensor configurator platform, and thus, the SQLite is unlikely to cause performance issues. In addition, Django supports multiple databases and switching the database is straightforward.

Safety, which is an important factor in the industry, was not in the focus in the development of the platform. Currently, the data is sent unencrypted over HTTP, MQTT or SDTP protocols and sensors fetch their updates without encryption. In addition, the platform has

not been comprehensively tested, which exposes it to vulnerabilities. However, the safety of the platform will be considered in the further development of the platform.

As the platform is aimed to be suitable for various use cases, the next step in the development of the platform is to add support for multiple application layer protocols and communication technologies. In addition, benchmarking tools for the assessment of the protocols could be added. Thereafter, the platform could be used to verify the results of the literature review of the most suitable application layer protocols and communication technologies.

The general problem in the selection of IoT platform is that there is an overwhelming amount of them with seemingly similar features. In addition, the same functionality can be implemented in several ways, which further complicates the comparison of platforms (Guth et al., 2016, p. 1). The developed platform stands out from other IoT platforms with the ease of use, the possibility of adding new sensors coding-free, and light-weightiness (focus only on the management of the sensor nodes).

6.2 Communication

The literature review of application protocols and communication technologies presents the most suitable and already established standards for transmission of the measurement data from a physical twin to a digital twin. The focus on the data collection leaves a significant part of the communication needs identified out of the scope of this thesis. However, this limitation is necessary, as it is not feasible to examine all areas of communication in a satisfactory manner in the context of this thesis. Furthermore, there is a great need for additional research of each of these communication needs.

The number of standards related to application layer protocols and communication technologies is overwhelming, and, in addition, new standards are constantly released. Therefore, it is not possible to review all of them in the context of this thesis. For example, some industrial standards such as ISA100.11 (Li et al., 2017, p. 1509) were left out. However, the most common standards are included in the literature review.

There is a lack of comprehensive comparisons of both application layer protocols and communication technologies in the scientific literature, which makes the assessment of them challenging. In addition, existing comparisons are often based on literature review and, thus, there is a need for additional field tests to verify results. The comparison of communication methods in this thesis is also based on solely literature review. However, the field tests could be executed in the next phase of the research project after support for several protocols is added to the sensor configurator platform.

The literature review shows that there exist suitable standards and protocols for sensor data transmission. While some examined standards are better suited for a digital twin than others, practical choices often dictate the choice between them. For example, the availability of libraries is important when choosing application layer protocols, and the existing network infrastructure when choosing communication technology. Therefore, for example, only Wi-Fi was implemented to the SCP, even though the used microcontrollers supported also LoRa, Sigfox, and NB-IoT.

While none of the standards is superior to each other, the developers often choose the one they are familiar with. Without a common decision to use a certain protocol, the use of

protocols remains diverse. This thesis recommends using the following application layer protocols:

1) DDS for real-time applications
2) MQTT for periodic data collection in stable networks
3) CoAP for periodic data collection in lossy networks

In addition, the following communication technologies are recommended:

1) Wi-Fi 802.11n for real-time applications
2) Wi-Fi 802.11n for periodic data collection if an easy implementation is the most important factor
3) Bluetooth for periodic data collection if the movement area of the physical twin is limited to a few tens of meters and energy consumption has to be low
4) LoRaWAN for periodic data collection if the movement area of the physical twin is not limited and energy consumption has to be low

6.3 Digital twin

The concept of digital twin, which came to the public only a few years ago, is still at its infancy. In the scientific literature, there is no unanimity of the features and the definition of a digital twin. The research field greatly influences to which features of a digital twin are being emphasized. For example, aeronautics is interested in forward simulations of systems, whereas manufacturing is interested in optimizing their process. For this reason, this thesis recommends creating a framework for identifying the core functionalities of a digital twin, after which a reference architecture of a digital twin could be derived. This allows the further development of the concept by enabling collaboration between fields and converging the existing visions of a digital twin.

The expectations towards a digital twin are set high as it is expected to offer numerous benefits throughout the product life cycle. Thus, the concept has gained huge popularity lately, and, actually, it is at the phase of inflated expectations in the hype curve (Panetta, 2018a). It is clear that some features of a digital twin such as the ability to completely mirror the state of physical twin are not feasible in practice. However, a digital twin is constantly developed, and the number of papers published has increased rapidly. In addition, a digital twin is not a completely new concept and it is built on top of the concepts presented already at the beginning of the 2000s indicating that there is a real need for the concept. Despite the constant development and need for a digital twin, there is a lack of realizations of a digital twin.

What makes the realization challenging, is the complexity of a digital twin and the numerous functionalities it offers. A digital twin consists of a set of linked systems working collaboratively together with external systems to offer these functionalities. Therefore, the interoperability between systems a digital twin consists of and external systems is fundamental. To enable this interoperability, standardized interfaces and protocols for communication between systems are required. However, there is a lack of standardization with digital twins as well as with IoT in general (Al-Qaseemi et al., 2016). The standardization of the communication is prerequisite for the emergence of digital twins. This thesis responds to the need of standardization by presenting the most suitable and already established standards for the transmission of the measurement data from a physical twin to a digital twin and by developing a platform, which allows the utilization of these most suitable standards.

The developed platform takes the DigiTwin project towards its goal of building a digital of an overhead crane by enabling the data collection from the physical twin. The platform

allows attaching sensors nodes to the physical crane effortlessly, and their remote management. In addition to the platform, this thesis also presented the most suitable application layer protocols and communication technologies for sensor data transmission from a physical twin to digital twin. The results can be utilized when designing the communication of the digital twin of an overhead crane. Other communication needs of a digital twin were also identified. These needs should be taken into account when designing the overall architecture of the digital twin. However, each of these communication needs identified requires more research.

This thesis can be considered successful because it helps the DigiTwin project to reach its goals and fulfills its purpose of examination of sensor data transmission from a physical to a digital twin. The thesis presented a comprehensive literature review on application layer protocols and also the most commonly used communication technologies. The literature review is not limited to the context of a digital twin and can be as a general guide when selecting IoT protocols. Therefore, the thesis has significance also in the field of IoT in general. Finally, the thesis narrows the gap between a concept of a digital twin and its realization by presenting a single ready-to-use system for a set of systems a digital twin consists of.

7 Conclusion

Digital twin is a digital counterpart of a physical object, which accurately mirrors the current state of its corresponding physical twin. It further develops concepts of smart products presented at the beginning of the 2000s. The definition of a digital twin is not yet established in the scientific literature and varies depending on the field as can be seen from Table 2.

The thesis focused on the communication between a digital twin and its physical counterpart, and more specifically on transmission of data collected from physical twin to a digital twin. This focus area was chosen because one of the key properties of a digital twin is an ability to accurately mirror its corresponding physical twin, which requires constant monitoring of the physical twin via sensors. Two distinct use cases for data collection from an overhead crane were derived. In the first use case sensor data is used to control the location of the hook in real-time and in the second use case the sensor data is used to monitor the stress of the bridge.

The literature review of communication focused on examining the most suitable application layer protocols and communication technologies for the selected use cases. The examined application layer protocols were HTTP, MQTT, CoAP, XMPP, AMQP, DDS, and OPC UA. The most suitable protocol for the first use case is DDS, as it capable of real-time communication, offers built-in security, and has low latency. For the second use case, MQTT, CoAP, and MQTT have the most suitable properties including low bandwidth, memory, and CPU usage. MQTT has the best availability of open-source libraries, which makes its implementation easier than CoAP and AMQP. Therefore, it is the preferred choice for the second use case. However, because CoAP uses UDP as underlying transport layer protocol instead of TCP, it is the recommended choice for lossy networks.

The examined communication technologies included 4G, 5G, NB-IoT, LoRaWAN, Sigfox, Bluetooth, 802.11ah, 802.11n, ZigBee, Z-Wave, and WirelessHART. For the first use case, Wi-Fi 802.11n is the recommended choice as it offers the lowest latency. For the second use case, there is not a single the most suitable option. However, Wi-Fi 802.11n is the recommended choice because of its easy implementation. Other suitable options are Bluetooth and LoRaWAN, because of their low energy consumption.

A sensor configurator platform was developed as part of this thesis. The platform narrows the gap between the concept of a digital twin and its realization by enabling data transmission from a physical twin to a digital twin. It allows the management of sensors remotely over the internet and offers a REST API interface that the subsystems of a digital twin and external systems can use. User tests on the platform were promising and indicated that the platform is easy to use. The developed platform benefits the DigiTwin project as it allows data collection from the overhead crane, which is prerequisite for creating the digital twin of the crane.

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List of appendices

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Appendix 2. Instructions given in user tests. 1 page.
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Appendix 1. An example of micropython file generated by the Sensor configurator platform.

```
import gc
import pycom
import socket
import micropython
import utime
import machine
import _thread
import ustruct
import uos
from machine import RTC, I2C, Timer
from network import WLAN
CONNECTION_BROKEN = -1
MAXLINE = 1024 #maximum number of bytes read with one recv command
FAILURE = -1
SUCCESS = 1
SENSOR_ID = 110
SENSOR_KEY = 'Y2u1KvWPVqbsC9WrICqF'
SOFTWARE_VERSION = '110_2019_03_05_09_18_50.txt'
SETTINGS_DICT = {}
SETTINGS_DICT['DATA_SEND_RATE_S'] = 60.0
SETTINGS_DICT['BURST_LENGTH'] = 0.0
SETTINGS_DICT['BURST_RATE'] = 0.0
SETTINGS_DICT['UPDATE_CHECK_LIMIT'] = 3600.0
SETTINGS_DICT['UPDATE_IP_ADDRESS'] = '86.50.143.154:8000'
SETTINGS_DICT['IP_ADDRESS_SEND'] = '86.50.143.154:2500'
SETTINGS_DICT['ADDRESS'] = 83
SETTINGS_DICT['SAMPLE_RATE_HZ'] = 1.56
SETTINGS_DICT['BAUDRATE'] = 100000
SETTINGS_DICT['FORMAT_STRING'] = '<hhhL'
SETTINGS_DICT['NETWORK_SETTINGS'] = ['TP_Link_Arch', (WLAN.WPA2, 'aiicnet3'),
'Pycom110']
SETTINGS_DICT['PATH'] = '/data/sensor/id/111'
READ_DICT = {}
READ_DICT['50'] = 6
WRITE_DICT = {}
WRITE_DICT['56'] = 0
WRITE_DICT['45'] = 59
WRITE_DICT['44'] = 4
WRITE_DICT['49'] = 8
"""Sends error message to the userinterface"""
def send_error_msg(error_type):
    network = connect_network(flash_light=False) #Connect to network
    ip_address, port = SETTINGS_DICT["UPDATE_IP_ADDRESS"].split(":")
    s = create_and_connect_socket(ip_address, port)
    content_length = len("sensor_id={}&sensor_key={}&status={}".format(
    SENSOR_ID, SENSOR_KEY, error_type))
    data = """POST /report_failure HTTP/1.1\r\nHost: {}\r\nContent-Type:
    application/x-www-form-urlencoded\r\nContent-Length:
    {}\r\n\r\nsensor_id={}&sensor_key={}&status={}\r\n\r\n""".format(ip_address
    , content_length, SENSOR_ID, SENSOR_KEY, error_type)
    s.send(bytes(data, 'utf8'))
    utime.sleep(2)
    print("Status sent to user interface")
"""Calculates how many bytes are read from sensor"""
def calculate_length():
    read_dict = READ_DICT
    sum = 0
```

```
53      for key in read_dict:
54          sum += read_dict[key]
55      return sum
56  """Writes the given value-address pairs to the attached sensor"""
57  def config_sensor(i2c):
58      address = SETTINGS_DICT["ADDRESS"]
59      write_dict = WRITE_DICT
60      for key in write_dict:
61          i2c.writeto_mem(address, int(key), write_dict[key])
62  """Reads the given amount of data form the socket"""
63  def read_data(s, length):
64      data = s.recv(length)
65      while len(data) < length:
66          data += s.recv(len(data) - length)
67      return data
68  """Read values from sensor"""
69  def read_values(i2c):
70      address = SETTINGS_DICT["ADDRESS"]
71      read_dict = READ_DICT
72      readed_values = b""
73      for key in read_dict:
74          readed_values += i2c.readfrom_mem(address, int(key), read_dict[key])
75      return readed_values
76  """Helper function to send data. Checks that every byte is sent.""" #From:
    https://docs.python.org/3/howto/sockets.html#socket-howto
77  def sender(s, data, length):
78      try:
79          totalsent = 0
80          while totalsent < length:
81              sent = s.send(data[totalsent:])
82              if sent == 0:
83                  print("socket connection broken")
84                  return CONNECTION_BROKEN
85              totalsent = totalsent + sent
86          return totalsent
87      except:
88          print("Data sending failed")
89          return CONNECTION_BROKEN
90  """Sync clock from NTP server"""
91  def sync_rtc(rtc):
92      rtc.ntp_sync("0.fi.pool.ntp.org", update_period=100) #sync clock from NTP
        server every 100 seconds
93      #max no. of cycles = 10
94      i = 0
95      while not rtc.synced() and i < 10:
96          utime.sleep(0.5)
97          i += 1
98  """Asks update from sensor configurator with HTTP request. If a new main.py is
    returned writes it to the new_main.py and reboots the board"""
99  def write_new_main(ip_address, port):
100     try:
101         addr = socket.getaddrinfo(ip_address, int(port))[0][-1]
102         s = socket.socket()
103         s.connect(addr)
104         content_length = len("sensor_id={}&sensor_key={}&software_version={}".
            format(SENSOR_ID, SENSOR_KEY, SOFTWARE_VERSION))
105         string = """POST /get_update HTTP/1.1\r\nHost: {}\r\nContent-Type:
            application/x-www-form-urlencoded\r\nContent-Length:
            {}\r\n\r\nsensor_id={}&sensor_key={}&software_version={}\r\n\r\n""".
            format(ip_address, content_length, SENSOR_ID, SENSOR_KEY,
            SOFTWARE_VERSION)
106         s.send(bytes(string, 'utf8'))
107         data_read = b""
108         while True:
```

```
109                 data = s.recv(MAXLINE)
110                 if data:
111                     data_read += data
112                 else:
113                     break
114             s.close()
115             decoded_data = data_read.decode('ascii')
116             payload_begins = decoded_data.find("import") #Payload string always
                begins with an import statement
117             if payload_begins == -1:
118                 if decoded_data.find("UP-TO-DATE") != -1:
119                     print("Software up-to-date")
120                     return
121                 else:
122                     print("There's an error with the server response")
123             else:
124                 data = decoded_data[payload_begins:]
125                 f = open("new_main.txt", "w")
126                 f.write(data)
127                 f.close()
128                 print("Writing data succeed!")
129                 #Confirm that data is received
130                 s = socket.socket()
131                 s.connect(addr)
132                 content_length = len("sensor_id={}&sensor_key={}".format(SENSOR_ID,
                    SENSOR_KEY))
133                 confirmation = """POST /confirm_update HTTP/1.1\r\nHost:
                    {}\r\nContent-Type:
                    application/x-www-form-urlencoded\r\nContent-Length:
                    {}\r\n\r\nsensor_id={}&sensor_key={}\r\n\r\n""".format(ip_address,
                    content_length, SENSOR_ID, SENSOR_KEY)
134                 p = s.send(bytes(confirmation, 'utf8'))
135                 s.close()
136                 print("update confirmed")
137                 utime.sleep(1)
138                 machine.reset()
139         except:
140             print("Software update failed.")
141 """Sends data to the given socket and returns total amount of bytes sent"""
142 def send_data(data, s, length):
143     bytes_sent = 0
144     for value_pair in data:
145         ts_packed = ustruct.pack("<L", value_pair[1])
146         sent = sender(s, value_pair[0] + ts_packed, length)
147         if sent == CONNECTION_BROKEN:
148             return CONNECTION_BROKEN
149         else:
150             bytes_sent += sent
151     return bytes_sent
152 """Connect to wifi"""
153 def connect_network(flash_light=True):
154     if flash_light:
155         pycom.heartbeat(False)
156     ssid, auth, identity = SETTINGS_DICT["NETWORK_SETTINGS"]
157     wlan = WLAN(mode=WLAN.STA)
158     wlan.connect(ssid=ssid, auth=auth, identity=identity)
159     while not wlan.isconnected():
160         if flash_light:
161             pycom.rgbled(0xCD7300) #Orange
162         utime.sleep(0.5)
163         if flash_light:
164             pycom.rgbled(0x00000)  # Black
165         utime.sleep(0.5)
166     return wlan
```

```
"""Closes WLAN"""
def close_network(network):
    network.disconnect()
    network.deinit()
"""Creates socket and connects to it. Returns socket"""
def create_and_connect_socket(ip_address, port): #port is a string
    try:
        s = socket.socket()
    except OSError:
        print("Socket cannot be created, resetting board")
        machine.reset()
    while True:
        try:
            s.connect(socket.getaddrinfo(ip_address, int(port))[0][-1])
            break
        except:
            pass
    return s
"""This function takes care that correct messages are sent to server"""
def communicate_with_server(data_with_ts, length, header_ts, rtc):
    try:
        ip_address, port = SETTINGS_DICT["IP_ADDRESS_SEND"].split(":")
        network = connect_network() #Connect to network
        sync_rtc(rtc)
        s = create_and_connect_socket(ip_address, port)
        data_string = "[\n"
        for value_pair in data_with_ts:
            data_string += "{\n"
            value_no = 1
            data_tuple = ustruct.unpack(SETTINGS_DICT["FORMAT_STRING"][:-1] ,
            value_pair[0])
            for value in data_tuple:
                data_string += "\t'Value" + str(value_no) + "':" + str(value) +
                "\n"
                value_no += 1
            data_string += "\t'Timestamp':" + str(value_pair[1]) + "\n"
            data_string += "},\n"
        data_string += "]"
        content_length = len("sensor_id={}&sensor_key={}&Timestamp={}&data=".
        format(SENSOR_ID, SENSOR_KEY, header_ts))
        content_length += len(data_string)
        string = """POST {} HTTP/1.1\r\nHost: {}\r\nContent-Type:
        application/x-www-form-urlencoded\r\nContent-Length:
        {}\r\n\r\nsensor_id={}&sensor_key={}&Timestamp={}&data={}\r\n\r\n""".
        format(SETTINGS_DICT["PATH"], SETTINGS_DICT["IP_ADDRESS_SEND"],
        content_length, SENSOR_ID, SENSOR_KEY, header_ts, data_string)
        s.send(bytes(string, 'utf8'))
        s.close()
        close_network(network)
    except OSError:
        print("OSError")
        try:
            if not network:
                network = connect_network() #Connect to network
            if not s:
                ip_address, port = SETTINGS_DICT["UPDATE_IP_ADDRESS"].split(":")
                s = create_and_connect_socket(ip_address, port)
            content_length = len("sensor_id={}&sensor_key={}&status=OSError".
            format(SENSOR_ID, SENSOR_KEY))
            data = """POST /report_failure HTTP/1.1\r\nHost: {}\r\nContent-Type:
            application/x-www-form-urlencoded\r\nContent-Length:
            {}\r\n\r\nsensor_id={}&sensor_key={}&status=OSError\r\n\r\n""".format
            (ip_address, content_length, SENSOR_ID, SENSOR_KEY)
            s.send(bytes(data, 'utf8'))
```

```
220                 utime.sleep(2)
221                 print("status send to user interface")
222                 print("resetting machine")
223                 machine.reset()
224             except:
225                 print("resetting machine")
226                 machine.reset()
227 """Loop measurement and control often data is sent to server"""
228 def measure(i2c):
229     print("Measure close network")
230     m = Measure(i2c)
231
232 class Measure:
233     def __init__(self, i2c):
234         self.i2c = i2c
235         self.data_with_ts = []
236         self.current_no_of_measurements = 0
237         self.no_of_measurements = int(round(SETTINGS_DICT["DATA_SEND_RATE_S"] *
            SETTINGS_DICT["SAMPLE_RATE_HZ"]))
238         self.rtc = RTC()
239         self.rtc.init((2018, 7, 17, 10, 30, 0, 0, 0))
240         network = connect_network()
241         sync_rtc(self.rtc)
242         close_network(network)
243         self.length = calculate_length()
244         self.start = utime.ticks_cpu()
245         self.header_ts = self.rtc.now()
246         self.new_header_ts = self.rtc.now()
247         self.period_time_us = int(round((1/SETTINGS_DICT["SAMPLE_RATE_HZ"]) *
            1000000))
248         self.__alarm = Timer.Alarm(self._measurement, us=self.period_time_us,
            periodic=True)
249
250     #Called every period_time_us
251     def _measurement(self, alarm):
252         try:
253             data = read_values(self.i2c)
254             timestamp = utime.ticks_diff(self.start, utime.ticks_cpu())
255             self.data_with_ts.append([data, timestamp])
256             self.current_no_of_measurements += 1
257             if self.current_no_of_measurements == self.no_of_measurements:
258                 self.header_ts = self.new_header_ts
259                 _thread.start_new_thread(communicate_with_server, (self.
                    data_with_ts.copy(), self.length, self.header_ts, self.rtc))
260                 self.new_header_ts = self.rtc.now()
261                 self.data_with_ts = []
262                 self.start = utime.ticks_cpu()
263                 self.current_no_of_measurements = 0
264                 utime.sleep(0.05) #Making sure that thread is created
265         except OSError as e:
266             print(e)
267             pycom.heartbeat(False)
268             _thread.start_new_thread(send_error_msg, ("I2CError",))
269             if e.args[0] == "I2C bus error":
270                 for i in range(10):
271                     pycom.rgbled(0xFF0000)  # Red
272                     utime.sleep(0.5)
273                     pycom.rgbled(0x883000)  # Orange
274                     utime.sleep(0.5)
275             else:
276                 _thread.start_new_thread(send_error_msg, ("OSError",))
277                 for i in range(10):
278                     pycom.rgbled(0xFF0000)  # Red
279                     utime.sleep(0.5)
```

```
280                     pycom.rgbled(0x00000)  # Black
281                     utime.sleep(0.5)
282                 machine.reset()
283             except MemoryError as e:
284                 gc.collect()
285                 print(e)
286                 pycom.heartbeat(False)
287                 _thread.start_new_thread(send_error_msg, ("MemoryError",))
288                 for i in range(10):
289                     pycom.rgbled(0xFF0000)  # Red
290                     utime.sleep(0.5)
291                     pycom.rgbled(0x0000FF)  # Blue
292                     utime.sleep(0.5)
293                 machine.reset()
294     """Asks updates at the given interval. Connects to network before asking
        updates"""
295     def ask_updates(interval, ip_address, port):
296         while True:
297             network = connect_network()
298             write_new_main(ip_address, port)
299             close_network(network)
300             utime.sleep(interval)
301     def main():
302         try:
303             print("Entering main loop")
304             i2c = I2C(0, I2C.MASTER, baudrate=SETTINGS_DICT["BAUDRATE"])
305             config_sensor(i2c)
306 
307             ip_address, port = SETTINGS_DICT['UPDATE_IP_ADDRESS'].strip().split(":")
308             network = connect_network()
309             write_new_main(ip_address, int(port))
310             close_network(network)
311 
312             _thread.start_new_thread(measure, (i2c,))
313             interval = SETTINGS_DICT['UPDATE_CHECK_LIMIT']
314             _thread.start_new_thread(ask_updates, (interval, ip_address, int(port)))
315         except OSError as e:
316             print(e)
317             pycom.heartbeat(False)
318             _thread.start_new_thread(send_error_msg, ("I2CError",))
319             if e.args[0] == "I2C bus error":
320                 for i in range(10):
321                     pycom.rgbled(0xFF0000)  # Red
322                     utime.sleep(0.5)
323                     pycom.rgbled(0x883000)  # Orange
324                     utime.sleep(0.5)
325             else:
326                 _thread.start_new_thread(send_error_msg, ("OSError",))
327                 for i in range(10):
328                     pycom.rgbled(0xFF0000)  # Red
329                     utime.sleep(0.5)
330                     pycom.rgbled(0x00000)  # Black
331                     utime.sleep(0.5)
332             machine.reset()
333 main()
```

Appendix 2. Instructions given in user tests.

GROUP 1

Instructions:

- Ask help only, if you absolutely can't proceed without it
- Go to 86.50.143.154:8000
- Log in with username: Group1
- Password: Some1234
- Select *Instructions* from the top panel, choose *Add sensor* and follow instructions
- Information needed for sensor configuration:
    - Data server ip address: 86.50.143.154:2500
    - Update check ip address: 86.50.143.154:8000
    - Sensor model: ADXL 345
    - Sample rate 12.5 Hz
    - Communication technology: Wlan
    - Instance: Aiic_war_room
    - Protocol: LWDTP
    - Instance: Testi LWDTP
    - (If setting is not mentioned here leave it as a default)
- Wifi name: wipy-wlan-f848
- If status does not change from Waiting-for-update to Measuring in 15 seconds ask for help.
- When you are finished, inform supervisor.
- Answer questionnaire: bit.ly/sensorconfigurator or using QR-code

Appendix 3. Results of user tests.

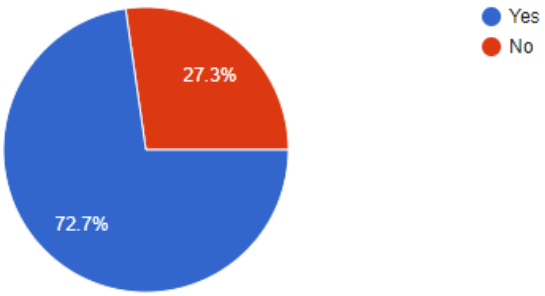
Group number

11 responses

5
10
2
8
11
3
6
9
13
12
7

Did the data sent by the sensor appear in the UI?

11 responses



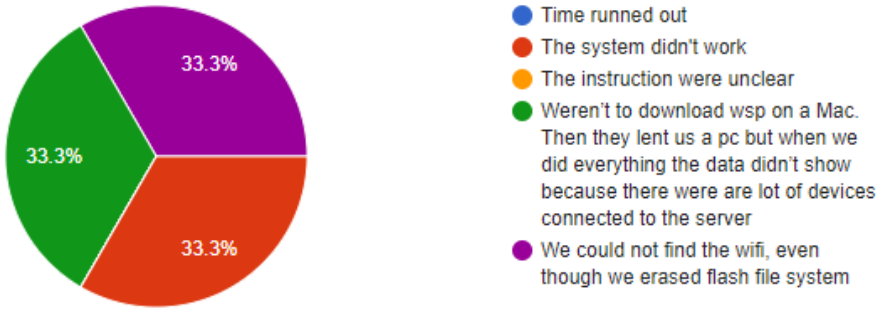
What was the last phase you accomplished?

3 responses

Measuring
Getting to the measuring point but we're unable to read the data
Moving initial files to microcontroler

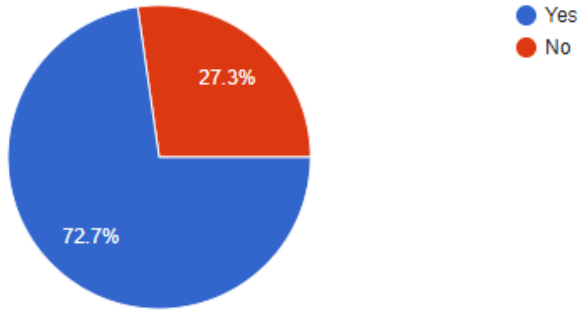
Why you weren't able to get sensor data shown in the UI?

3 responses



Did you ask help?

11 responses

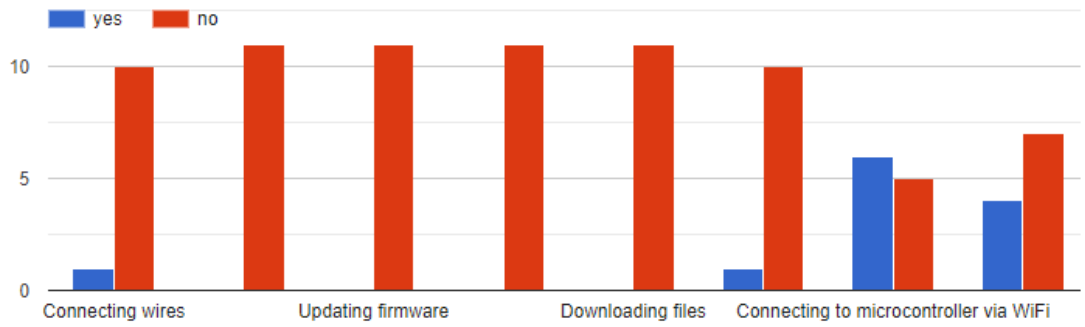


Why did you ask help?

8 responses

Because there was problem with wifi sensor
We should have read the instructions till the end. There is one question where you switch tabs and you should proceed with the previous tab
It was not working
There were some problems with connection
We forgot to connect aalto wifi
Trouble using the Mac version of wsp
because it did not worked
Why it crushes?

Did you encounter any problems during the following phases?



If you answered "yes" in the previous question, could you describe the problem and how should it be fixed?

7 responses

Reseting by plug in and plug out power to wifi sensor
We were connected to the Aalto Wifi, but should have been connected to the microcontroller
At the beginning it was impossible to connect at wifi of microcontroller but finally we managed to do it using the university wifi.
We connected the wires in the wrong place and then we changed it
Changing laptop
No
We move wrong file with another name(we couldn't delete it), and all crushed

Did you have any other problems during configuration?

8 responses

No
no
/

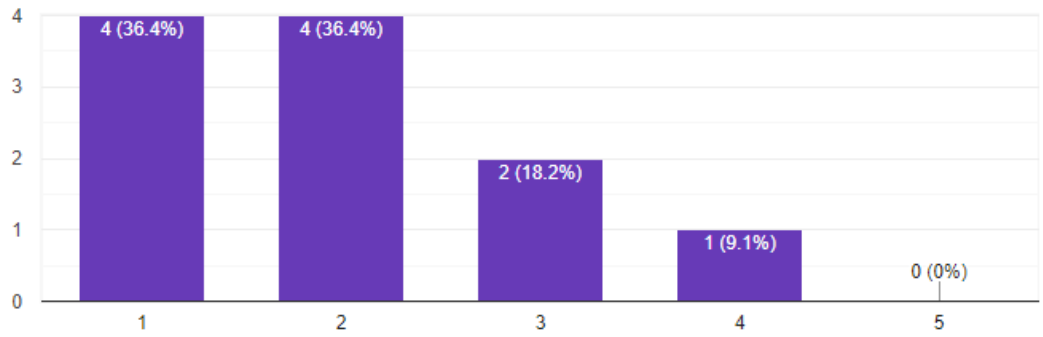
Do you have any suggestions for improvement of the configurator?

10 responses

No
no
Not any, it's super cool!
Make sure there is no duplicate in sensors ID
Maybe open the page "add sensor" in a different tab and mention that you go back to the instructions
Possibility of work with a Mac server
We move wrong file with another name(we couldn't delete it), and all crushed

How easy was it to use the system?

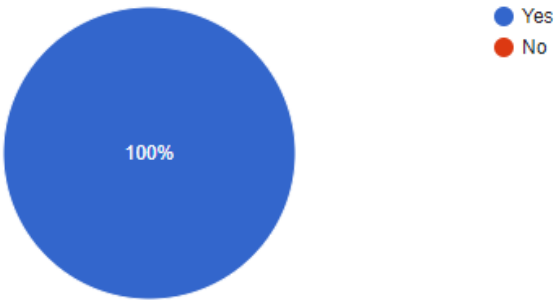
11 responses



(1=Very easy, 5=Very difficult)

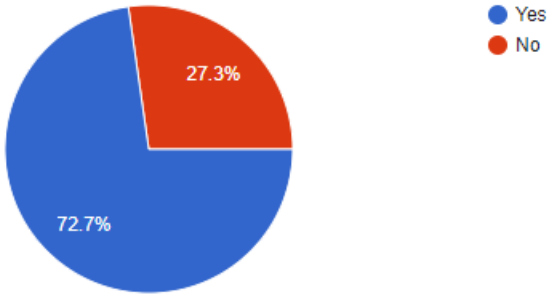
Do you think that the configurator is useful?

11 responses



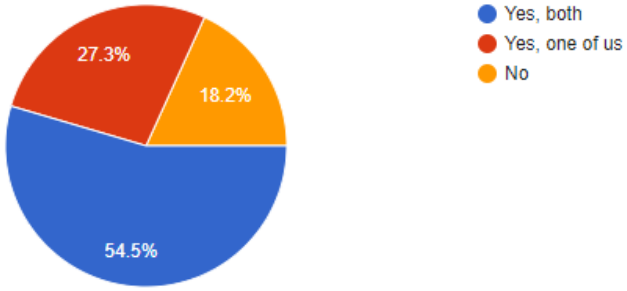
Would you use system like this in the future?

11 responses



Would you contribute this kind of project, if the code was open source?

11 responses



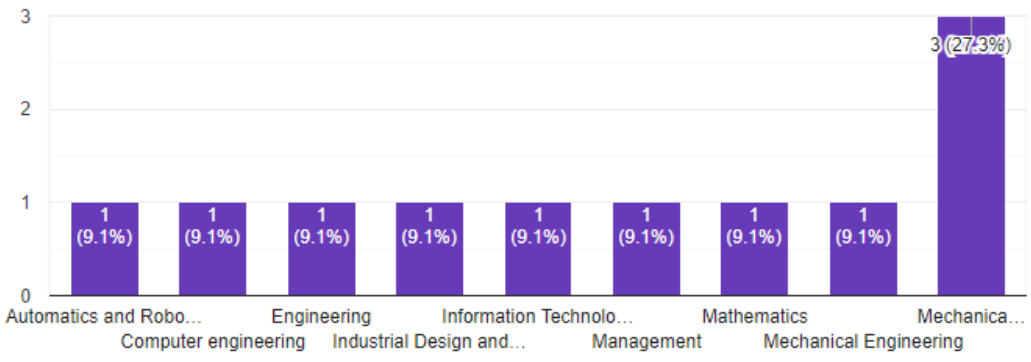
Is there any other feedback you would like to give?

6 responses

Nice experience, should be easier to see the output.
Thank for your help. Even if we couldn't solve the problem, we know what is the source of it and we learned something interesting
Good explaination
It was interesting that we had this task because at our university we didn't have the opportunity to do it till now.
Thank you for this great experience
It's interesting things, thank you:)

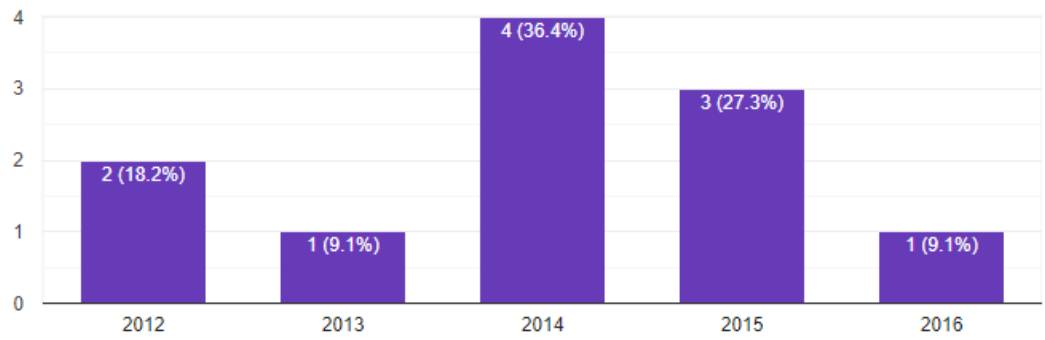
Field of study, student number 1

11 responses



Starting year of the studies, student number 1

11 responses



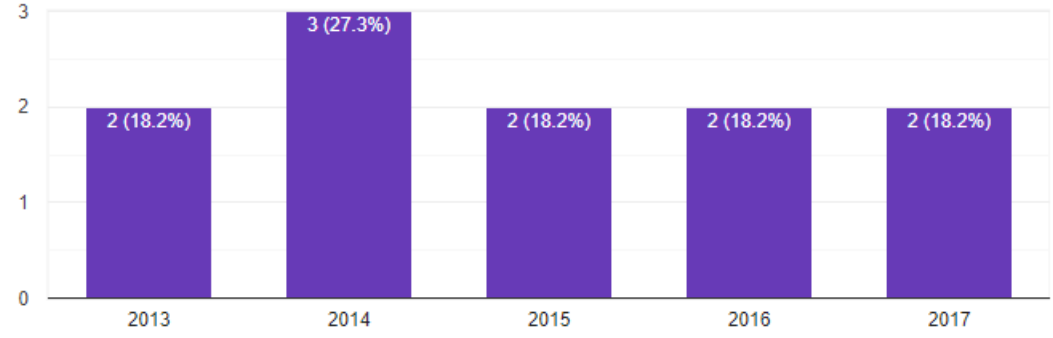
Field of study, student number 2

11 responses

Bioengineering
Engineering physics
Electromechanical engineering, Energy
Industrial Eng. and Management
Civil engineering
Mathematics
Mechatronic engineering
Engineering
Computer engineering
Mechanical engineering
Applied Mathematics

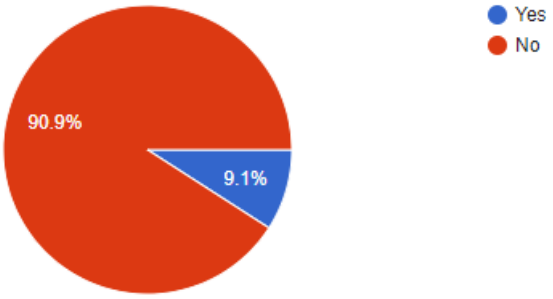
Starting year of the studies, student number 2

11 responses



Have you previously used a system that resembles this configurator?

11 responses



If you answered yes to the following question, could you describe the system you have used?

1 response

Arduino

Do you have previous experience from using microcontrollers?

11 responses